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MEMORANDUM REPORT NO. 2737

(Supersedes IMR No. 478)

WIND TUNNEL EXPERIMENTS ON THE EFFECT OF COMBUSTION IN THE WAKE REGION OF SUPERSONIC PROJECTILES - TEST SERIES III

J. Richard Ward
Frank P. Baltakis
Dennis J. Mancinelli

April 1977

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This report summarizes the third set of wind tunnel tests to evaluate the effect of combustion of pyrotechnics on the base drag of supersonic projectiles. In this test series, a larger diameter model was used to expand the range of injection parameters for R20C. It was found that the base pressure rise vs I, the injection parameter, for R20C could be correlated by an expression requiring two parameters. The maximum base drag reduction achieved with pyrotechnics at M_∞ = 2.0 was 68%. → next page

M sub infinity

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The maximum specific impulse at M_{∞} = 2.0 was nearly 8kN-s/kg. The maximum specific impulse was observed at an $\bar{I}$ value of 0.002. Direct measurement of the specific impulse by means of a force balance agreed with the specific impulses computed from integrating base pressure-time histories.

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LIST OF SYMBOLS

A	area of the base of the wind tunnel model
C_{Db}	base drag coefficient
ΔC_{Db}	change in C_{Db} due to combustion
df	diameter of the fumer cavity
d	diameter of the wind tunnel model
I	injection parameter
Isp	specific impulse
J	constant used in the correlation of base drag reduction and the injection parameter
ℓ	length of burning column
M	Mach number
m	mass
$\dot{m}$	mass burning rate
P	pressure
P_b	base pressure
P1...P8	pressure tap designation
ΔP_b	change in base pressure due to combustion
$\Delta(P_b/P_\infty)$	change in the ratio of base pressure to free-stream pressure due to combustion
ρ	density
r	linear burning rate
U	air speed
T	temperature
tb	burning time

Subscripts

i	initial conditions
c	during combustion
f	fumer mix
ig	igniter mix
∞	free-stream conditions
o	stagnation conditions

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I. INTRODUCTION

This report summarizes the results from the third set of wind tunnel tests to evaluate how effectively pyrotechnics reduce projectile base drag. Previous experiments[1,2] concentrated on pyrotechnic formulations similar to those used in tracer rounds, since such formulations were expected to ignite and burn at subatmospheric pressure. The main objective of the present tests was to examine a variety of fuels and oxidizers as potential fumer mixes. In addition, some earlier experiments were repeated with a 64mm diameter model in place of the standard 25mm diameter model. Tests were also made with a force balance to compare specific impulses computed from pressure measurements with specific impulses measured directly with the force balance.

II. EXPERIMENTAL

Test Facility

The experiments were conducted in a wind tunnel at Mach 2 at duplicated sea-level pressure and temperature conditions. The facility used was the Naval Surface Weapons Center's Hypersonic Tunnel which has a large capacity air supply and heating system. Normally, this tunnel is operated at Mach numbers 5 to 10. Recently it has been equipped with two additional stilling chambers which permit its operation at supersonic Mach numbers at duplicated sea-level temperature and pressure conditions. The flow nozzles used in this study were of centerbody-type design, 15 or 30cm exit diameter and were procured specifically for projectile base flow studies. The overall tunnel system and the new stilling chamber were depicted previously.[1,2] The test setup is illustrated on Figure 1. Wind tunnel conditions for each test run are given in Table I.

Model and Instrumentation

Projectile base flow was simulated using a bluff cylindrical model which was supported in the stilling chamber and extended through the nozzle throat into the test section (Figure 2). Two sizes, 25 and 64mm diameter models were used. Model lengths, measured from the nozzle throat, were 26.7cm and 46cm for the 25mm and 64mm diameter models, respectively.

Both models were equipped with air turbines capable of spin rates of up to 50 krpm and with force balances for direct base drag measurements (Figure 3). Pressure orifices were provided near the model periphery for base drag determination during tests with spin.

---

[1] *J. R. Ward, F. P. Baltakis, S. W. Pronchick, "Wind Tunnel Study of Base Drag Reduction by Combustion of Pyrotechnics," BRL Report No. 1745, October 1974, (AD #B000431L).*

[2] *J. R. Ward, F. P. Baltakis, D. Mancinelli, and T. Elmendorf, "Wind Tunnel Experiments on the Effect of Combustion in the Wake Region of Supersonic Projectiles," BRL Memorandum Report No. 2588, February 1976, (AD #B009982L).*

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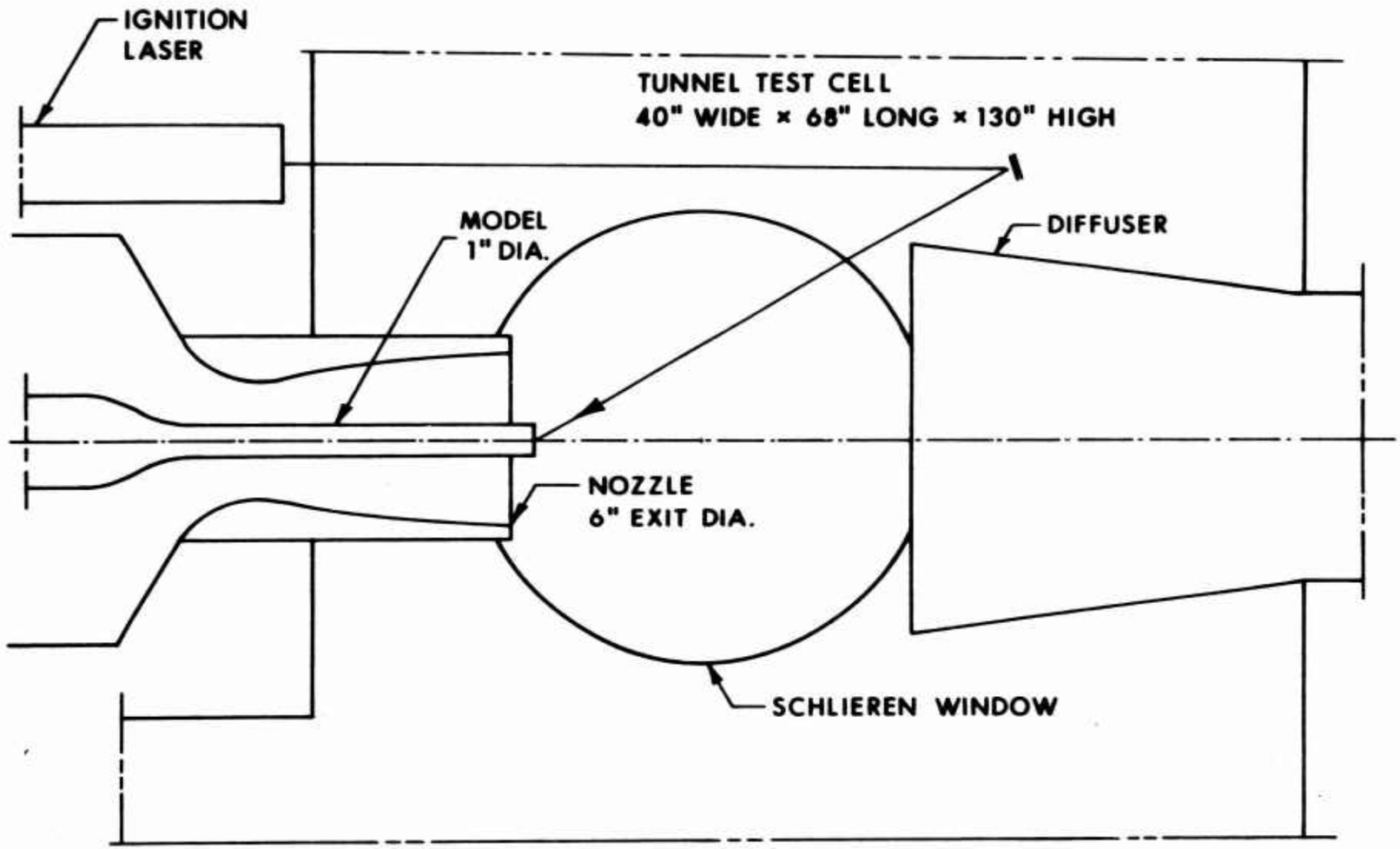

Figure 1. Wind Tunnel Test Setup

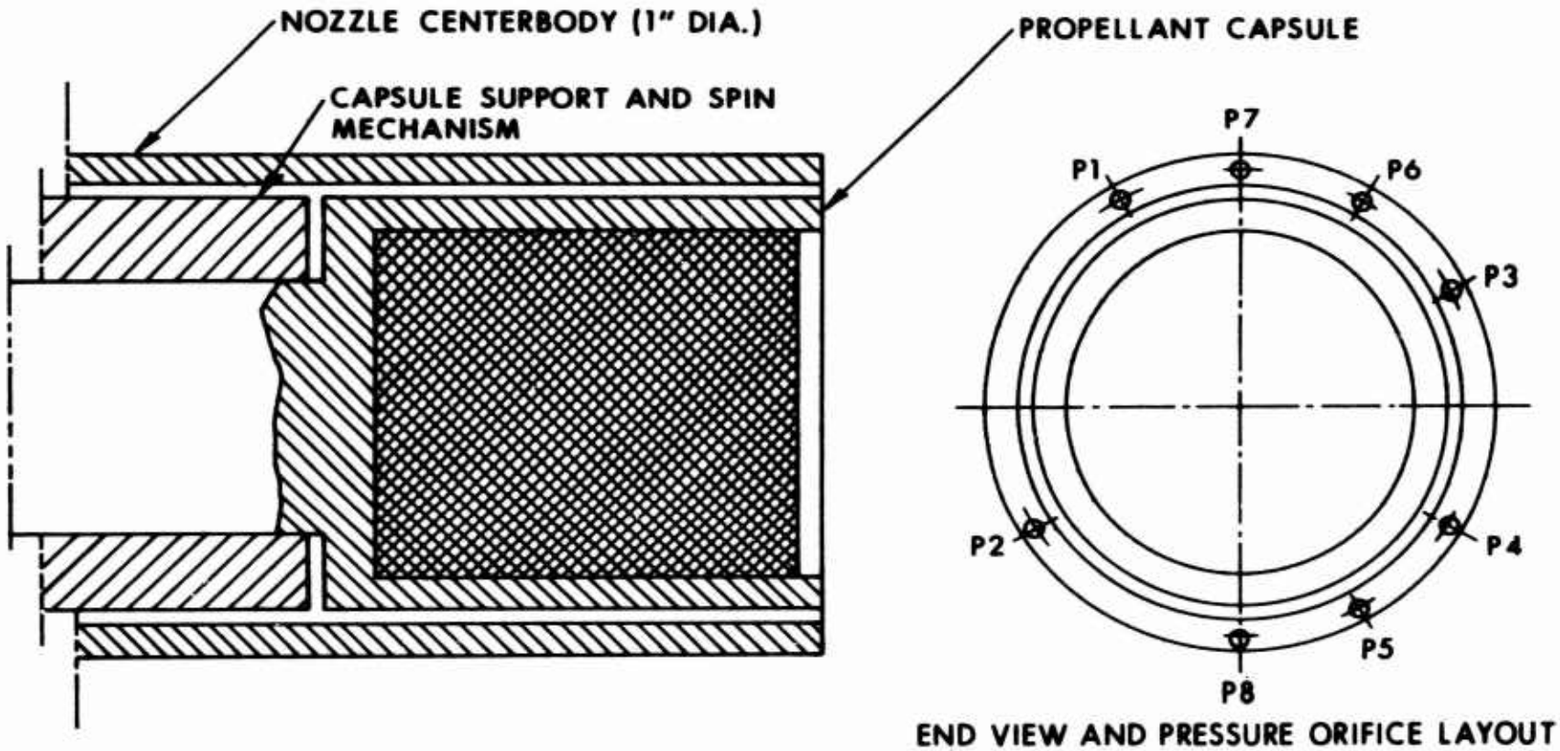

Figure 2. Pressure Orifice Location and Fumer Capsule

TABLE I. Summary of Test Conditions

Run	M_∞	P_o, bar	T_o, K	Fumer Composition, Percent by Weight	Remarks
18	1.97	6.4	483	R20C	64mm diameter model
19	1.97	6.5	489	R20C	64mm diameter model
49	1.97	6.6	486	R20C	64mm diameter model, spinning at 18 krpm.
51	1.97	6.9	489	R20C	Force balance test
52	1.97	6.8	492	R20C	Force balance test
53	1.97	6.9	492	R20C	Force balance test
54	1.99	6.8	492	$NaBH_4/Sr(NO_3)_2$, 40/60	
56	1.99	6.8	472	$NaBH_4/Sr(NO_3)_2$, 15/85	
57	1.99	7.0	484	$NaBH_4/Sr(NO_3)_2$, 25/75	
58	1.99	7.1	489	$NaBH_4/Sr(NO_3)_2$, 35/65	
59	1.99	6.7	489	$ZrH_2/Sr(NO_3)_2$, 70/30	No ignition
60	1.99	7.0	492	$Zr/H_2/Sr(NO_3)_2$, 50/50	No ignition
61	1.99	6.8	489	$MgH_2/Sr(NO_3)_2$, 24/76	No ignition
62	1.99	7.0	494	Mg/SrO_2/oxamide, 14/81/5	No ignition
63	1.99	6.9	492	F-4/azocel, 90/10	Delayed ignition
64	1.99	6.7	494	F-4/azocel, 90/10	Delayed ignition
65	1.99	6.9	494	F-4	Delayed ignition
66	1.99	7.0	494	E-B[a]	
67	1.99	7.0	494	E-B[a]	
68	1.99	6.9	494	$NaBH_4/Sr(NO_3)_2$, 25/75	
69	1.99	6.9	494	$NaBH_4/Sr(NO_3)_2$, 35/65	

Table I (Continued)

Run	M_∞	P_o, bar	T_o, K	Fumer Composition, Percent by Weight	Remarks
70	1.99	6.9	494	$B/BaCrO_4$, 15/85	No ignition
71	1.99	6.9	494	$B/KClO_4$, 31/69	
72	1.99	6.9	494	Mg/SrO_2/C.R.[b], 15/83/2	No ignition
73	1.99	6.9	494	$Zr/Sr(NO_3)_2$/C.R., 47/43/10	
74	1.99	6.9	494	$Zr/KClO_4$, 57/43	
75	1.99	6.9	494	$Zr/KClO_4$/C.R., 51/39/10	No ignition
76	1.99	6.9	494	$Ti/KClO_4$, 33/67	No ignition
77	1.99	6.9	494	$Mg/KClO_4$/C.R., 37/53/10	
78	1.99	6.9	494	$Zr/Sr(NO_3)_2$, 52/48	
79	1.99	6.9	494	Repeat Run 78	Delayed ignition
80	1.99	6.9	494	$Ti/Sr(NO_3)_2$, 36/64	No ignition
81	1.99	6.9	494	$Ti/Sr(NO_3)_2$/CR, 32/58/10	
82	1.99	6.9	494	F-4/RDX, 96/4	Delayed ignition
83	1.99	6.9	494	$NaBH_4/Sr(NO_3)_2$, 40/60	
84	1.99	6.9	494	$ZrH_2/Sr(NO_3)_2$, 50/50	No ignition
85	1.99	6.9	494	F-4/HES[c], 90/10	
86	1.99	6.9	494	$Ti/KClO_4$/CR, 30/60/10	
87	1.99	6.9	494	F-4, 149-250μ Mg	
88	1.99	6.9	494	F-4/TNT, 96/4	
89	1.99	6.9	494	$Ti/Sr(NO_3)_2$, 36/64	

Table I (Continued)

Run	M_∞	P_o, bar	T_o, K	Fumer Composition, Percent by Weight	Remarks
90	1.99	6.9	494	Ti,$KClO_4$, 33,67	No ignition
91	1.99	6.9	494	F-4,74-100μ Mg	
92	1.99	6.9	494	F-4,44-100μ Mg	
93	1.99	6.9	494	F-4,<44μ Mg	
94	1.99	6.9	494	B/$KClO_4$, 31/69	
95	1.99	6.9	494	Mg/SrO_2/CR, 15,83,2	No ignition

[a] Propietary mix from the Ensign-Bickford Co. Approximate composition in percent by weight

Mg(25± 5), $Sr(NO_3)_2$ (35± 5), PVC (10), DOP (10), AP(20) where

PVC is polyvinylchloride,
DOP is dioctylpthalate,
AP is ammonium perchlorate.

[b] Calcium resinate.

[c] Propellant supplied by Hercules Co. No analysis given.

The propellant for each run was contained in a separate steel capsule and was ignited with a laser light beam. A 250-watt CO_2 gas laser was used and arranged as shown on Figure 1. The light beam diameter at the plane of impingement was about one cm and the exposure time ranged from two to five seconds.

Fumer Mixes

The fumer mixes were charged at a pressure of 282 MN/m^2(40,900 psi) at the Frankford Arsenal's Pyrotechnics Laboratory. The pressure was calibrated with a Webster force gage. A layer of R20C mix was pressed onto each fumer mix to assist in the ignition of the mix. With the exception of experiments with fumer mixes R20C and F-4, the fumer mix consisted of a fuel and oxidizer or a fuel, oxidizer, and one burning rate modifier. The chemical composition of R20C and F-4 is included in Table II.

The mass and the column height of each fumer mix and igniter mix were also measured in order to calculate mass burning rates.

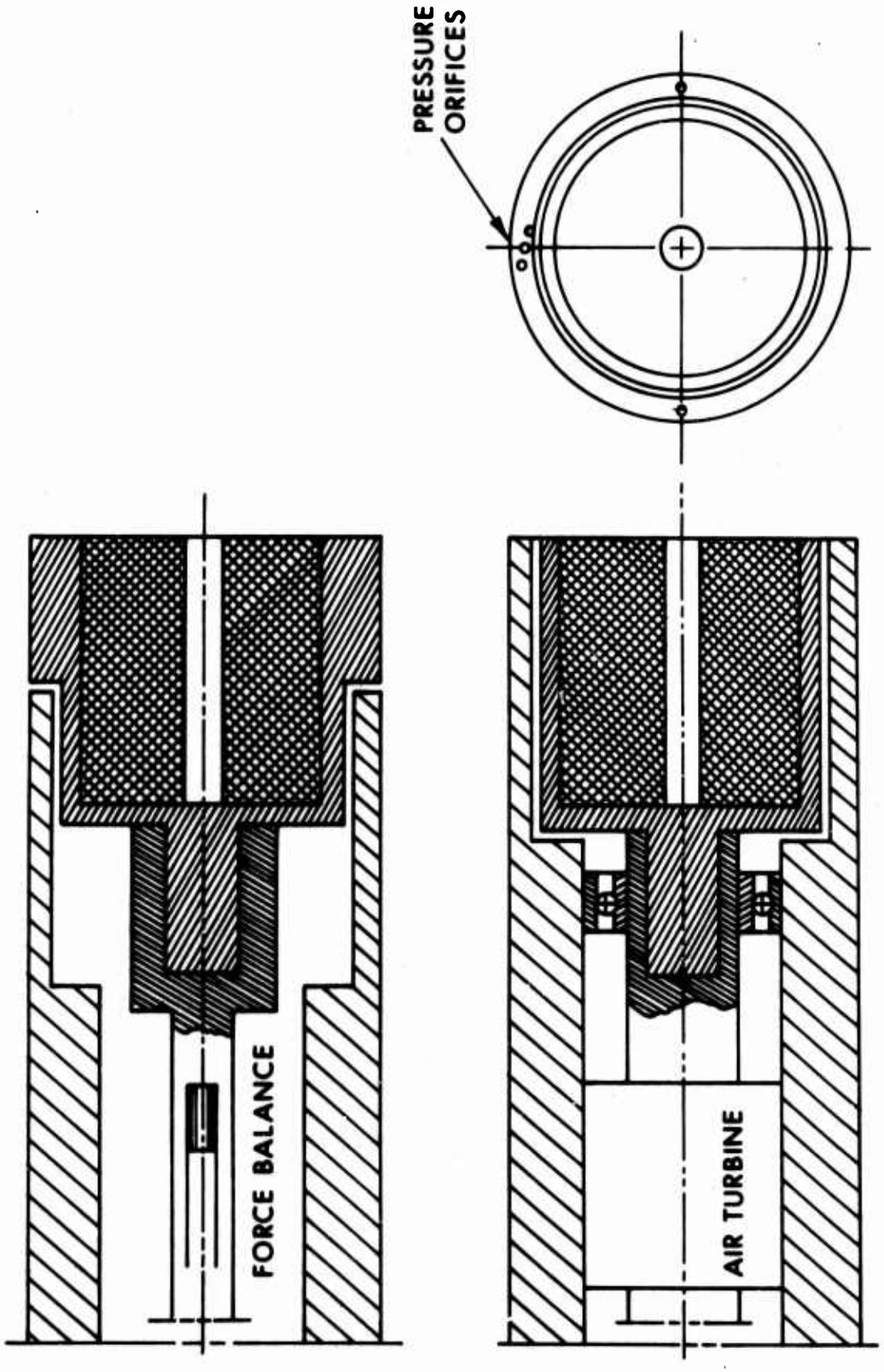

Figure 3. Diagram of the Fumer Capsule with the Force Balance and with the Spin Mechanism

Table II. Composition of Standard Fumer Mixes Examined in Wind Tunnel Experiments

Designation	Constituents, percent by weight	
R20C	Mg, grade 12[a],	21.5
	SrO_2	65.7
	PbO_2	3.4
	BaO_2	3.4
	C.R.[b]	6.0
F-1	Mg, grade 11[a]	8.1
	SrO_2	78.8
	C	4.0
	C.R.[b]	9.1
F-4	Mg, grade 11[a]	33.2
	$Sr(NO_3)_2$,	57.7
	C.R.[b]	9.1
R284	Mg, grade 11[a]	28.0
	$Sr(NO_3)_2$	55.0
	C.R.[b]	17.0

[a]Magnesium specification as given in Mil Spec JAN-M-382A.

[b]Calcium resinate.

III. RESULTS

Base Pressure Data

The performance parameters of primary interest in this work are base pressure increase and the fumer specific impulse. The base pressure increase was recorded directly versus time. The specific impulse was obtained by integrating the base pressure increase with respect to time and then multiplying by the ratio of A/m_f.

The base pressure increase was found to vary considerably with time. Mixes which ignited quickly generally yielded a step-type pressure pulse. Those mixes which ignited more slowly yielded gradual pressure increases.

Pressure-time histories for test runs which ignited are shown in the Appendix. The time is shown in seconds and the base pressure is normalized to the free-stream static pressure. For a number of runs only qualitative variation is shown. During these runs, due to malfunctioning of the data recording system, pressure data were recorded

using an auxiliary printing system and quantitative computer plotting was not available.

It may be noted on many runs that the main pressure rise is preceded by a sharp spike corresponding to the combustion of the igniter mix (R20C). In some runs the base pressure at the end of burning is higher than the pre-combustion value. Presumably this is from formation of slag on the face of the wind tunnel model that obstructed the pressure taps.

The reduction of the base drag coefficient during combustion is

$$\frac{\Delta C_{Db}}{C_{Db}} = \frac{\Delta P_b}{P_\infty - P_{b_i}} \quad . \tag{1}$$

For those tests in which the fumer mix ignited rapidly and burned evenly to yield step-like pressure-time histories, ΔP_b was constant over the run and the mass burning rate of the fumer mix could be inferred. For the tests which did not yield step-like pressure-time histories, the following expression was devised to estimate an average ΔP_b,

$$\Delta P_b = (tb)^{-1} \int_o^{tb} [(P_b)_t - (P_b)_i] \, dt \quad , \tag{2}$$

where P_{bt} is the base pressure at time t,

tb = time during which the base pressure is at least 25% greater than $(P_b)_i$.

For the majority of tests, the specific impulse was based on pressure data taken at orifice P3 (Figure 2). For some tests data from other pressure orifices were used. In most cases the agreement between the specific impulse values computed from data at different pressure taps was well within ±10 percent.

The injection parameter was computed from

$$I = \frac{\dot{m}}{\rho_\infty U_\infty A} \quad . \tag{3}$$

Force Balance Measurements

Direct measurements of the reduction in drag force by combustion were attempted with both the 25mm and 64mm diameter models. The force balance was designed originally for use with the 25mm diameter model. In the 64mm diameter model, the force balance was overloaded (Runs 11-17).

The force measurements were made with R20C, since this mix ignited easily and yielded step-like base pressure-time histories. All results pertinent to subsequent discussion are presented in Table III.

TABLE III. Summary of Test Results for Experiments in which Combustion Occurred

Run	m_f, g	m_{ig}, g	l_f, mm	l_{ig}, mm	ρ_f, g/cm^3	tb,s	I x 10^3	ΔC_{Db}	Isp, N-s/g[a]	
18	11.1	-	18.9	-	2.36	4.1	0.90	0.23	6.8	5.6(P1)
19	11.1	-	18.2	-	2.46	3.6	1.0	0.26	7.1	6.6(P1)
49	11.1	-	18.0	-	2.48	1.2	3.1	0.29	-	4.4(P6)
51	10.6	-	18.3	-	2.34	3.4	8.8	-	3.2, force[b]	
52	10.6	-	18.3	-	2.34	3.2	9.7	-	3.1, force[b]	
53	10.5	-	17.9	-	2.36	3.2	8.8	-	2.5, force[b]	
54	7.7	0.8	18.9	1.1	1.64	3.1	7.3	0.45	2.8	2.6(P2)
56	9.4	0.8	18.0	1.2	2.11	2.4	11.0	0.47	1.8	1.6(P2)
57	8.7	0.9	18.6	1.1	1.89	2.9	8.8	0.51	2.6	2.1(P2)
58	8.2	0.9	19.4	1.1	1.70	4.5	5.4	0.45	3.7	-
63	8.9	1.1	19.0	1.4	1.88	7.7	3.5	0.40	4.9	-
64	9.0	1.0	19.0	1.3	1.91	9.8	2.7	0.33	5.2	-
65	9.7	0.9	17.7	1.4	2.21	8.7	3.5	0.33	4.4	3.9(P2)
66	7.8	0.8	19.5	1.0	1.61	11.2	2.0	0.40	8.5	7.5(P2)
67	8.1	0.7	19.8	1.0	1.65	11.3	2.1	0.39	8.0	6.7(P2)
68	9.0	1.0	19.0	1.1	1.91	2.5	11.0	0.45	-	1.5(P1)
69	8.1	0.9	19.5	1.1	1.67	5.0	4.8	0.48	-	2.9(P1)
71	7.2	1.3	14.8	2.8	1.96	2.6	8.7	0.48	2.1	-
73	12.8	0.8	18.3	1.1	2.82	11.4	3.2	0.32	3.9	-
74	14.1	0.9	18.9	1.2	3.00	2.1	19.0	0.59	1.2	-

Table III (Continued)

Run	m_f, g	m_{ig}, g	l_f, mm	l_{ig}, mm	ρ_f, g/cm^3	tb,s	I x 10^3	ΔC_{Db}	Isp, N-s/g[a]	
77	8.0	0.8	18.0	1.1	1.80	13.4	1.8	0.31	7.0	-
78	14.7	0.8	17.8	1.0	3.32	2.2	19.0	0.49	1.0	-
79	8.2	0.8	18.0	1.2	1.84	8.7	2.8	0.46	6.4	-
81	11.6	0.6	18.4	0.94	2.54	2.7	12.0	0.57	1.8	-
82	8.2	0.9	17.8	1.3	1.86	8.7	2.8	0.38	5.4	-
83	7.9	0.6	19.3	0.4	1.65	4.4	5.1	0.51	3.9	-
85	8.4	0.8	18.1	1.1	1.87	11.6	2.1	0.33	5.8	-
86	10.2	0.6	18.7	0.6	2.20	18.1	1.6	0.20	4.8	-
87	8.2	1.0	17.8	1.3	1.86	13.4	1.8	0.26	5.5	-
88	8.4	0.8	17.1	1.2	1.98	6.8	3.7	0.40	4.2	-
89	11.2	0.7	17.9	0.9	2.53	17.0	1.9	0.20	4.3	-
91	7.9	1.0	17.1	1.4	1.86	8.6	2.8	0.38	5.4	4.5(P1)
92	7.9	0.9	16.6	1.4	1.91	8.1	2.9	0.39	5.2	4.6(P1)
93	7.8	0.8	16.4	1.2	1.92	7.1	9.4	0.46	5.7	4.5(P1)
94	6.1	1.4	13.4	1.5	1.84	2.4	8.5	0.49	2.3	-

[a] First entry is Isp measured from P3. Second entry is Isp measured from pressure orifice indicated.

[b] Isp from force balance measurement.

IV. DISCUSSION

In the previous wind tunnel tests,[2] it was shown that the base pressure increase due to combustion of the pyrotechnic could be correlated to the injection parameter. One objective of the present test series was to see if alternate fuels and oxidizers obeyed the same trend, or perhaps some combination would be superior to the base drag reductions observed to date. To properly compare the present tests with those in reference 2, one must separate the effect of the igniter mix on base pressure from the effect of the fumer mix. This can be done only if quantitative computer plots of base pressure vs time are available. Furthermore, it is necessary that the fumer mix have a constant mass burning rate in order to compute the injection parameter. Table IV lists the runs that satisfy these two criteria.

Table IV. Base Pressure for Tests in Which Combustion of the Fumer Could be Distinguished From the Igniter

Run	m_f, g	tb, s	$\dot{m}_f$, g/s	I x 10^3	$(P_b/P_\infty)_i$	$\Delta(P_b/P_\infty)$	% C_{Db} reduced
18	11.1	3.8	2.9	0.97	0.68[a]	0.067	21
19	11.1	3.6	3.1	1.0	0.68[a]	0.085	27
49	11.1	1.1	10.0	3.4	0.67[a,b]	0.16	48
56	9.4	1.4	6.7	18.0	0.62	0.26	68
57	8.7	1.8	4.8	13.0	0.62	0.23	60
66	7.8	9.4	0.83	2.2	0.62	0.16	42
67	8.1	9.3	0.87	2.4	0.62	0.17	45

[a] 64mm diameter model.

[b] Spin rate 18 krpm.

Runs 18, 19, and 49 were made with the 64mm diameter model. The object of these tests was to obtain base pressure measurements for R20C at lower values of I than could be obtained with the standard 25mm diameter model used in all the previous tests. Previous wind tunnel experiments with cold gases[3,4] and with pyrotechnics[2] demonstrated

[3] *J. Reid and R. C. Hastings, "The Effect of a Central Jet on the Base Pressure of a Cylindrical Afterbody in a Supersonic Stream," RAE Report No. Aero. 2621, 1959.*

[4] *L. D. Kayser, "Effects of Base Bleed and Supersonic Nozzle Injection on Base Pressure," BRL Memorandum Report No. 2456, March 1975, (AD #B003442L).*

that the base pressure increase for a given value of I is independent of d_f/d for I less than 0.005. Such results for gases injected into the wake are illustrated in Figure 4. As indicated in Table IV, the 64mm diameter model provides data for I values of 0.001 and 0.0034, within the region of I where the base pressure rise is independent of d_f/d.

In Figure 5 the base pressure increase is plotted as a function of I for all runs in the three wind tunnel test series with R20C. From Figure 5, it is evident that a maximum base pressure increase has been reached with values of I greater than 0.02, and that a sizeable increase in base pressure results for injection values below 0.005. The general trend of base pressure vs I exhibited in Figure 5 is similar to the trend for the injection of gases as in Figure 4.

Runs 56 and 57 were made with $NaBH_4$ as the fuel. Previous experiments[5,6] suggested that the injected gas should have as low a molecular weight as possible. To test this hypothesis with pyrotechnics, fumer mixes with MgH_2, ZrH_2, or $NaBH_4$ were made up with $Sr(NO_3)_2$ as the oxidizer. Only the fumer mixes with $NaBH_4$ ignited and burned in the wind tunnel, although all the hydrides burned under laboratory conditions. Two of the $NaBH_4$ mixes yielded rapidly igniting, step-like pressure histories from which burning rates could be inferred. These two runs are summarized below and the base pressure increases vs I plotted in Figure 6 with the previous data for R20C.

Fumer Mix, percent by weight	$\dot{m}_f$, g/s	I	$\Delta(P_b/P_\infty)$	r, cm/s
15/85 $NaBH_4/Sr(NO_3)_2$	6.7	0.018	0.26	1.3
25/75 $NaBH_4/Sr(NO_3)_2$	4.8	0.013	0.23	1.0

The faster burning 15/85 $NaBH_4/Sr(NO_3)_2$ provides the largest base pressure rise observed in these wind tunnel tests. The base pressure rise for spinning R20C is 0.24 vs 0.26 for the $NaBH_4$ mix. It appears nonetheless, that the values for $NaBH_4$ fit into the trend of base pressure rise vs I exhibited by the R20C runs (Figure 6). The trend of a maximum base pressure rise for a given value of I followed by decreasing base pressure rise as I increases is also observed for gases injected into the wake (e.g., Figure 4).

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5 *J. E. Bowman and W. A. Clayden, "Reduction of Base Drag by Gas Ejection," RARDE Report 4/69, December 1969.*

6 *S. N. B. Murthy and J. R. Osborn, "Base Flow Data With and Without Injection: Bibliography and Semi-Rational Correlations," BRL Contract Report No. 113, August 1973, (AD #914188L).*

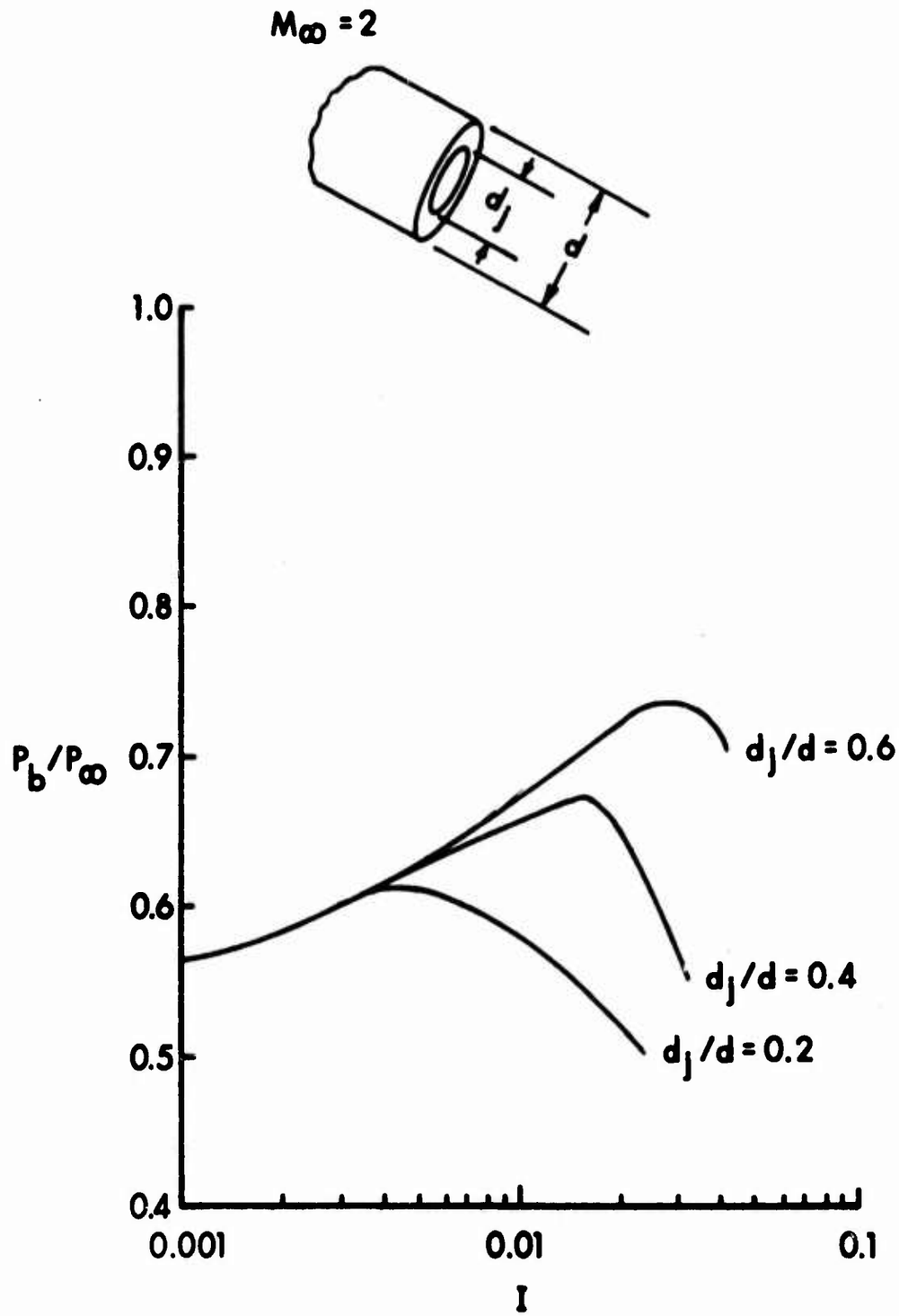

Figure 4. Summary of Reid and Hastings' Results with Various Values of d_f/d vs $\underline{I}$

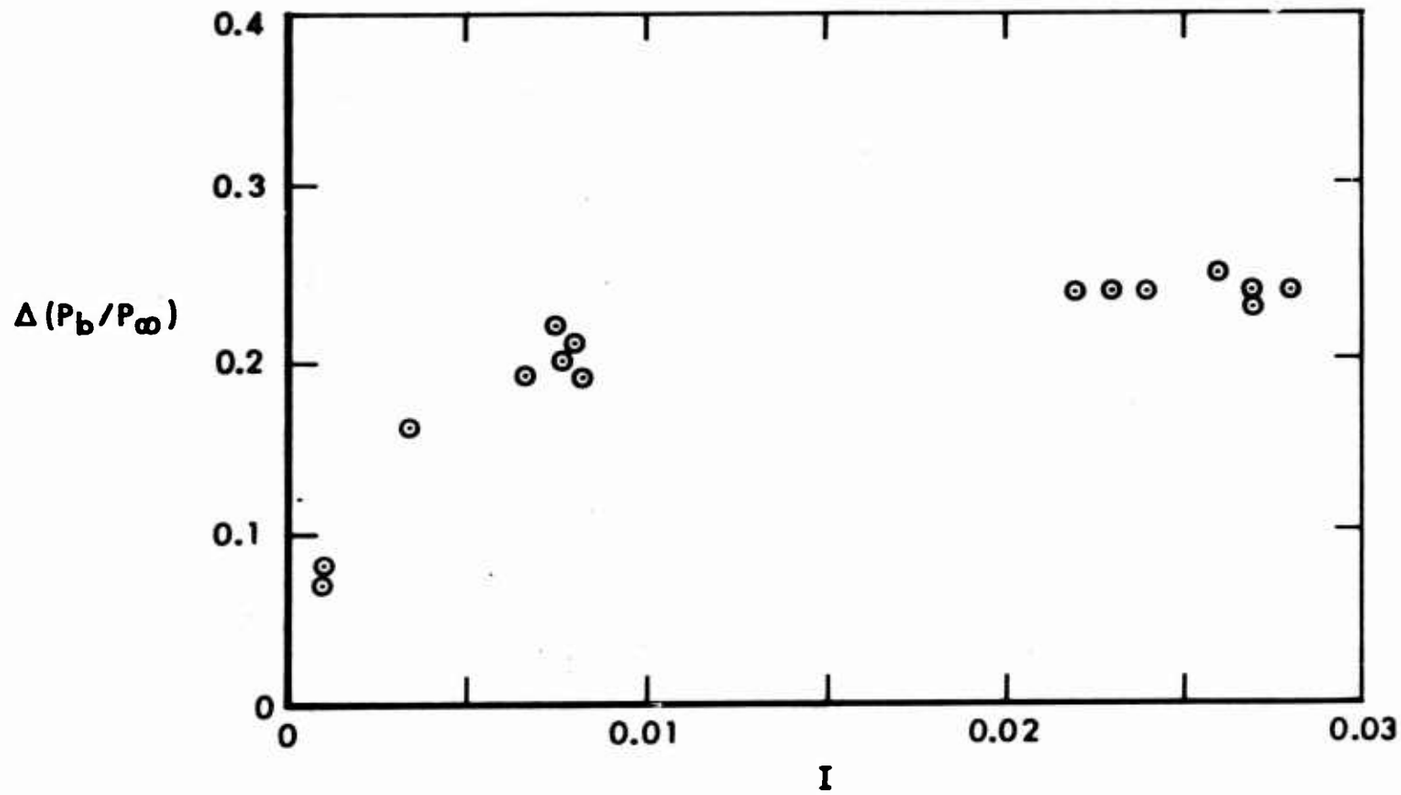

Figure 5. Increase in Base Pressure vs I for R20C

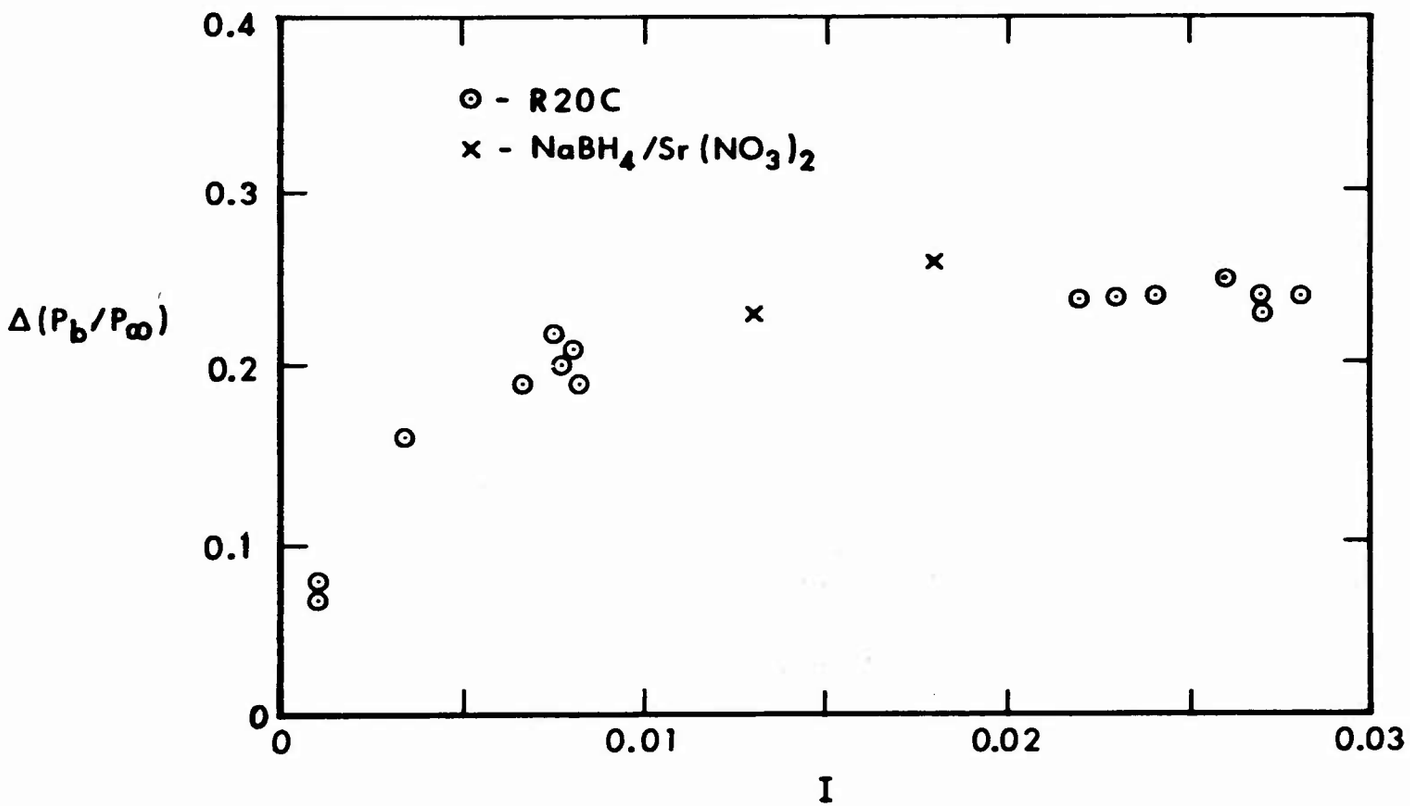

Figure 6. Increase in Base Pressure vs I for R20C and $NaBH_4/Sr(NO_3)_2$

The only other fumer mix for which quantitative computer output was available was a propietary mix containing ammonium perchlorate (AP) and strontium nitrate as the oxidizers. The $\Delta(P_b/P_\infty)$ for this mix is plotted in Figure 7 along with the base pressure increases for the mixes in Figure 6.

The marked increase in base pressure exhibited by fumer mixes with I values near 0.001-0.002 is reflected in the specific impulses for the fumer mixes in Table IV. The specific impulses are listed in Table III; the specific impulses listed for the $NaBH_4$-mixes and the AP-mix include the igniter. To estimate the specific impulse for the fumer mix itself, the specific impulse values in Table III are corrected as follows:

$$Isp_f = Isp_{(f+ig)} \frac{tb_f}{tb_{(f+ig)}} \frac{m_{(f+ig)}}{m_f} \quad . \tag{4}$$

A summary of the specific impulses for the fumer mixes in Table IV is presented in Table V and the specific impulses as a function of I are plotted in Figure 8. The maximum specific impulse occurs at relatively low values of I (approximately 0.002). In a situation where the quantity of fumer that can be added to a projectile is limited, the appropriate fumer mix should be one with an injection parameter near 0.002.

The next step in the analysis of the correlation between base pressure increase and the injection parameter is to see if a function can be found relating the base drag reduction to I. Bowman and Clayden[5] proposed the following expression for that purpose

$$C_{Db} = C_{Db_i} e^{-JxI} \quad . \tag{5}$$

The constant J varies with Mach number, and the temperature and molecular weight of the injected gas.

Bowman and Clayden stated that they were interested in a simple, empirical expression for use in systems analysis and their expression should be regarded as "tentative." From the results for pyrotechnic combustion, Bowman and Clayden's simple expression appears inadequate. Equation (5) implies that the base drag disappears at large values of I; this is not true for the pyrotechnics nor for ejection of various gases (e.g., Figure 4). Equation (5) should be more properly expressed as

$$C_{Db} = C_{Db_{min}} + (C_{Db_i} - C_{Db_{min}}) e^{-JxI}, \tag{6}$$

where $C_{Db_{min}}$ is the minimum base drag coefficient that may be achieved.

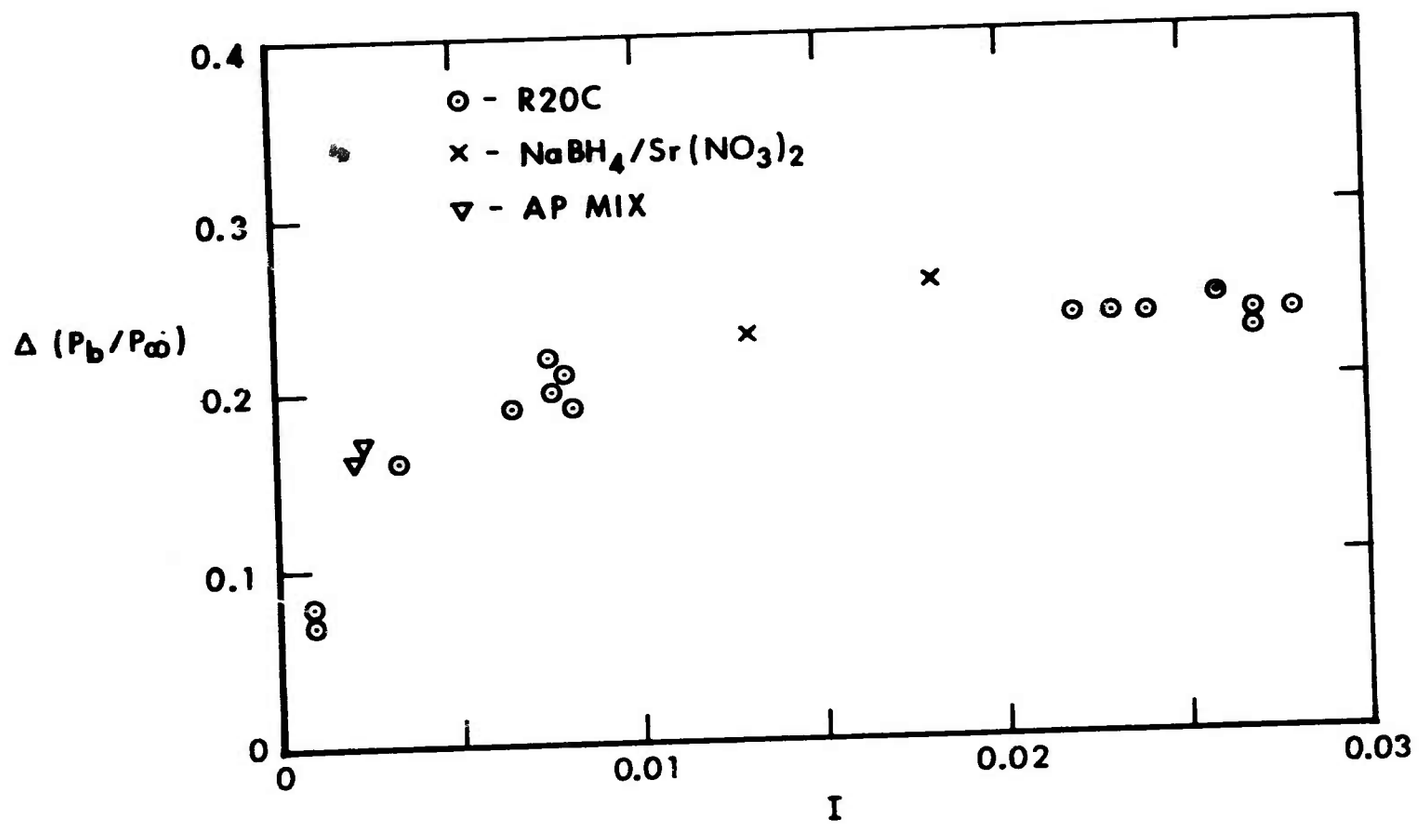

Figure 7. Increase in Base Pressure vs I for R20C, $NaBH_4/Sr(NO_3)_2$, and AP-Mix

TABLE V. Specific Impulses of Fumer Mixes in Table IV

Fumer Mix	Isp, kN-s/kg	$I \times 10^3$	Reference
R20C	6.8	1.0	a
R20C	7.1	1.0	a
R20C	4.4	3.4	b
R20C	3.0	6.7	b
R20C	3.4	7.5	b
R20C	3.2	8.0	c
R20C	2.2	8.2	b
R20C	2.6	8.7	b
R20C	1.2	23.0	b
R20C	1.4	23.0	b
R20C	0.95	24.0	b
R20C	0.94	26.0	b
R20C	1.1	27.0	b
R20C	1.3	27.0	b
R20C	1.1	28.0	b
AP-mix	7.8[d]	2.2	a
AP-mix	7.2[d]	2.4	a
$NaBH_4/Sr(NO_3)_2$ (15/85)	1.2[d]	18.0	a
$NaBH_4/Sr(NO_3)_2$ (25/75)	1.8[d]	13.0	a

[a] This work. [b] F. P. Baltakis, "Wind Tunnel Study of Projectile Base Drag Reduction Through Combustion of Solid, Fuel-Rich Propellants," NOL Wind Tunnel Report No. 93, October 1974. [c] Reference 1.

[d] Corrected value using Eq. (4).

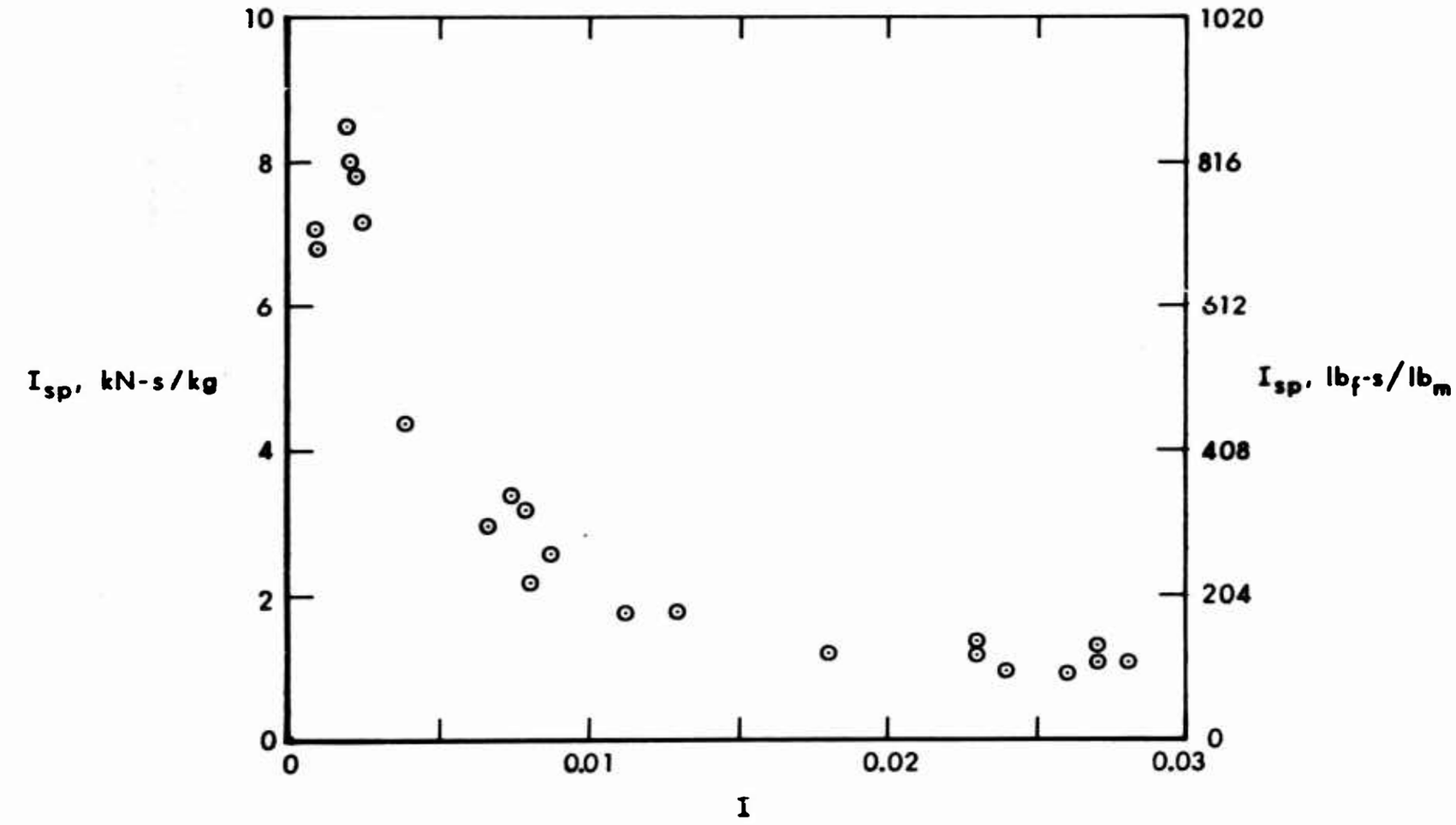

Figure 8. Specific Impulse vs I for Fumer Mixes from Table IV, M_∞=2.0

To test the applicability of equations (5) and (6) to the data generated in the wind tunnel tests, equations (5) and (6) were expressed in terms of $\Delta(P_b/P_\infty)$ through

$$C_{Db} = \frac{2(P_\infty - P_b)}{\rho_\infty U_\infty^2} \quad . \tag{7}$$

Equations (5) and (6) become

$$\Delta\left(\frac{P_b}{P_\infty}\right) = \left[1 - \left(\frac{P_b}{P_\infty}\right)_i\right] \left[1 - e^{-JxI}\right] \quad , \text{ and} \tag{8}$$

$$\Delta\left(\frac{P_b}{P_\infty}\right) = \Delta\left(\frac{P_b}{P_\infty}\right)_{max} \left(1 - e^{-JxI}\right) \quad , \tag{9}$$

where $\Delta\left(\frac{P_b}{P_\infty}\right)_{max}$ refers to the maximum base pressure that may be achieved.

A non-linear least-squares program[7] was used to fit equations (8) and (9) to the data in Figure 7. In equation (8), the initial value of P_b/P_∞ was 0.62. The best-fit value of J was computed for equation (8); for equation (9) best-fit values of J and $\Delta(P_b/P_\infty)_{max}$ were computed. The results of the calculations are presented below and the curves generated using the best-fit values are drawn through the experimental data in Figure 9.

Equation	J	$\Delta(P_b/P_\infty)_{max}$
(8)	66	-
(9)	3.9×10^2	0.23

Equation (8) underestimates the $\Delta(P_b/P_\infty)$ at low values of I and overestimates the base pressure increase at larger values of I. Equation (9) fits the experimental data much better, although the best-fit $\Delta(P_b/P_\infty)_{max}$ is less than the 0.26 recorded for the (15/85) $NaBH_4/Sr(NO_3)_2$ mix.

An alternate expression that also fits the experimental data as well as equation (9) is the following

$$\Delta(P_b/P_\infty) = \frac{QI}{1+NI} \quad , \tag{10}$$

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[7] *R. H. Moore and R. K. Ziegler, "The Solution of the General Least Squares Problem With Special Reference to High-Speed Computers," Los Alamos Scientific Laboratory Report LA-2367, March 1960.*

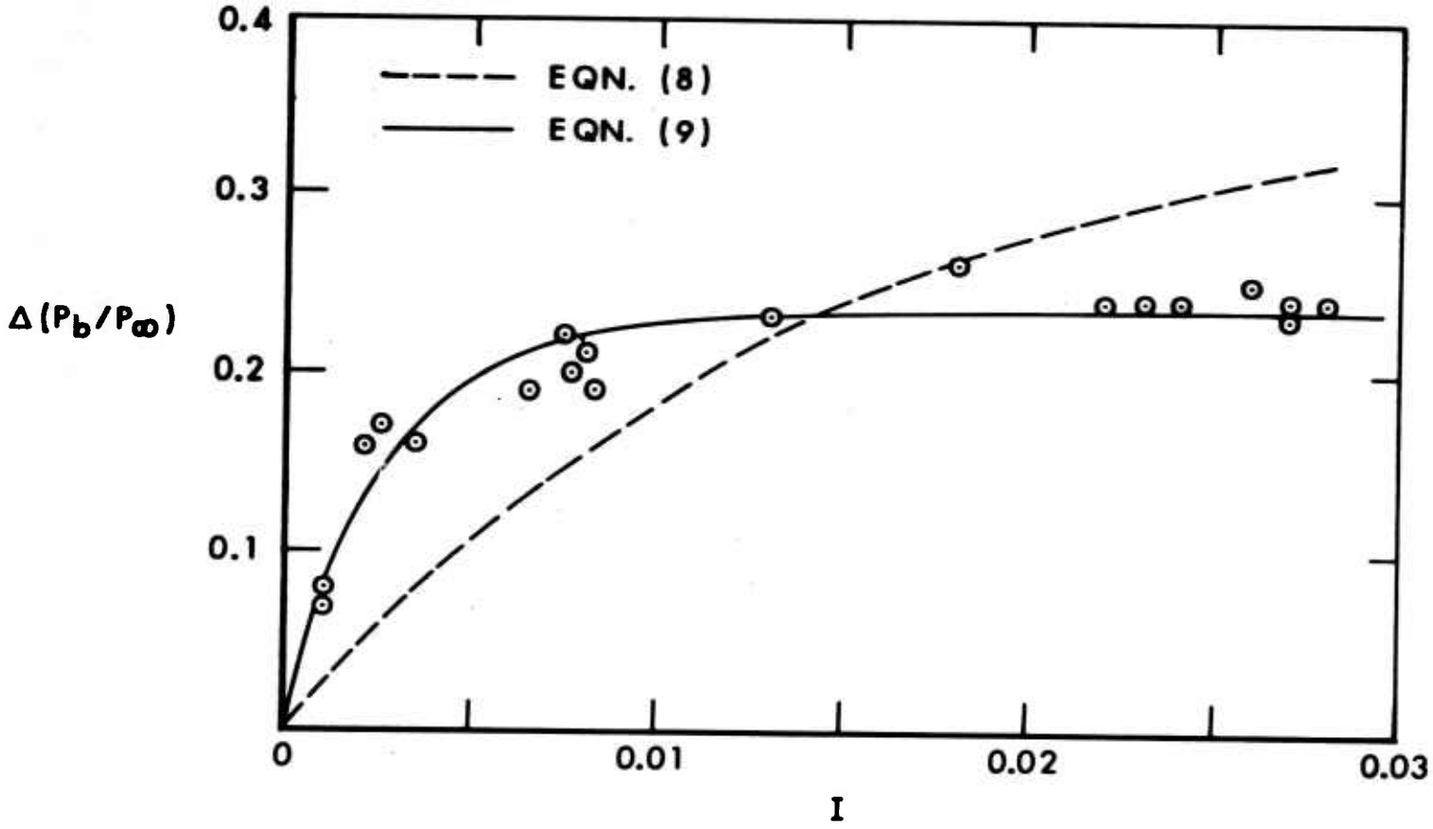

Figure 9. Increase in Base Pressure vs I

where Q and N are the floating parameters. In Figure 10 the curve generated from best-fit values of Q and N is drawn through the experimental points. For the data taken from Figure 7, best-fit values of Q and N are 1.4×10^2 and 5.2×10^2, respectively.

The remaining test runs in Table IV that merit discussion are those test runs made with the force balance. The object of these runs was to compare the specific impulses computed from the base pressure measurements with the specific impulses determined experimentally. Table VI compares specific impulses measured with R20C as the fumer mix with specific impulses computed from the base pressure measurements. The measured and computed specific impulses are in reasonable agreement. Thus, it appears the pressure distribution over the rear face of the wind tunnel model is uniform. Kayser[4] measured the pressure distribution over the face of his model while gas was being injected into the wake region and he found that the pressure increase was uniform.

The remaining tests can be treated only qualitatively either because the combustion of the fumer was irregular or because quantitative computer output was not available. In order to summarize these tests in a systematic manner, Table VII was constructed. For each combination of fuel and oxidizer, the following information is provided:

a. Run number.

b. Percent by weight of fuel.

c. Comment on the burning properties:

N - no combustion.

B - unsteady burning.

Q - smooth combustion, no quantitative output.

IV - smooth combustion, quantitative output, listed in Table IV.

For the tests in Table VII listed as smooth burning but with no quantitative output, the percent base drag reduction and injection parameter are listed in Table VIII. The longer the fumer mix burned, the less important is the failure to account for the igniter. For example, the injection parameter for Run 66 (AP-mix) changes only slightly when the correction is made for the igniter as shown below:

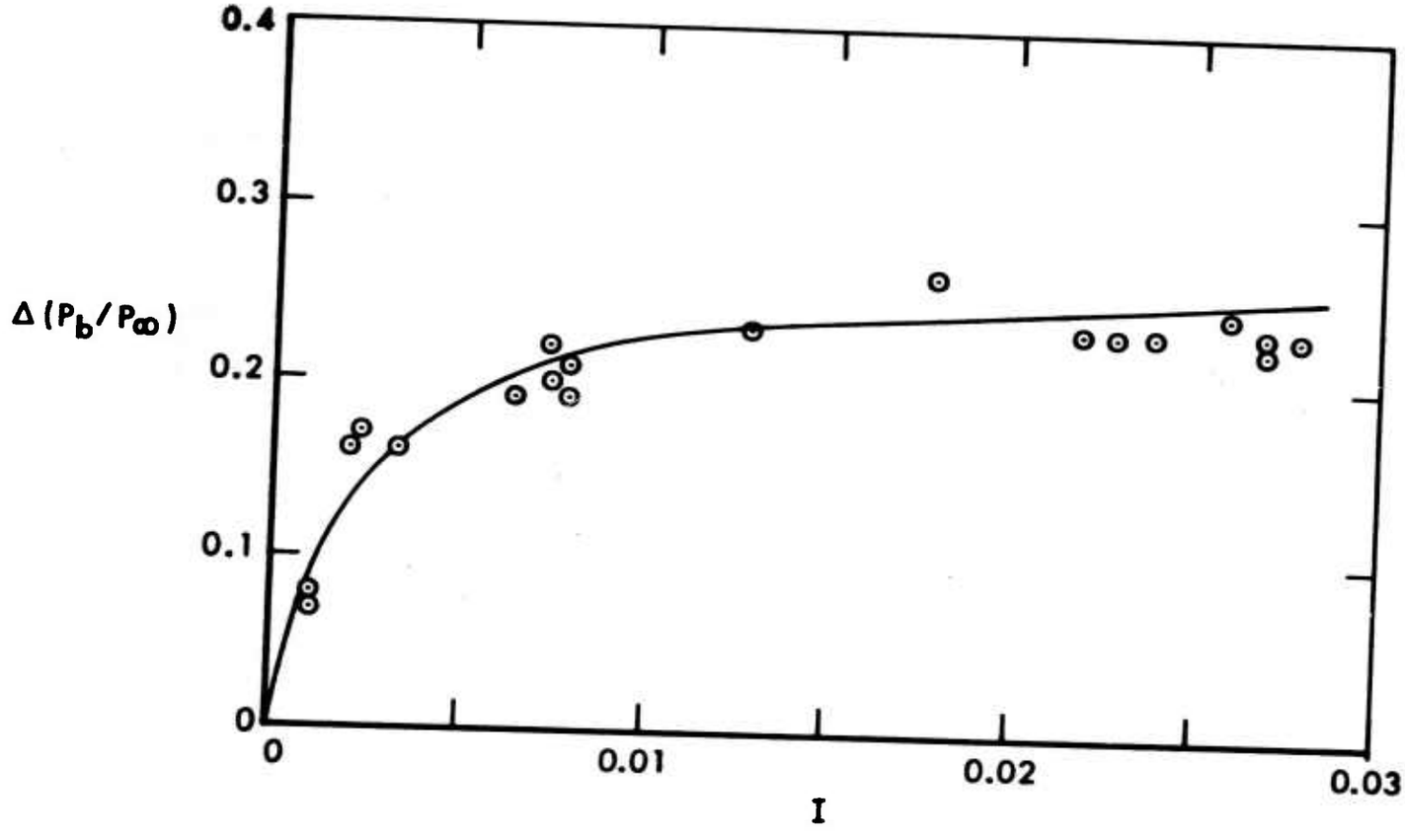

Figure 10. Increase in Base Pressure vs I with Equation (10)

TABLE VI. Comparison Between Specific Impulses Measured by the Force Balance with those Inferred from Pressure Orifices[a]

Run	$\dot{m}$, g/s	I	Isp, kN-s/kg	Reference
51(F)[b]	3.1	8.8	3.2	d
52(F)	3.3	9.7	3.1	d
53(F)	3.3	8.8	2.5	d
1(P)[c]	4.0	8.0	3.2	e
117(P)	3.6	8.0	3.2	f
119(P)	3.1	6.7	3.0	f
121(P)	3.7	8.2	2.2	f
112(P)	3.4	7.5	3.4	f
124(P)	4.0	8.7	2.6	f

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[a] Fumer mix is R20C, M_∞ = 1.98 or 1.99

[b] Specific impulse determined from force balance measurements.

[c] Specific impulse determined from pressure measurements.

[d] This work.

[e] Reference 1.

[f] F. P. Baltakis, "Wind Tunnel Study of Projectile Base Drag Reduction Through Combustion of Solid, Fuel-Rich Propellants," NOL Wind Tunnel Report No. 93, October 1974.

TABLE VII. Summary of Results for Various Fuel/Oxidizer Combinations Tested[a]

Oxidizer	$BaCrO_4$	$KClO_4$	$KClO_4$/C.R.[b]	$Sr(NO_3)_2$	$Sr(NO_3)_2$/C.R.
Fuel					
B	70/15/N	71/31/B 94/31/B			
$NaBH_4$				56/15/IV 57/25/IV 68/25/Q 58/35/B 69/35/B 54/40/B 83/40/Q	
Mg			77/37/Q 79/37/Q		
Ti		76/33/N 90/33/N	86/30/B	80/36/N 89/36/B	81/32/Q
Zr		74/57/Q	75/51/N	78/52/B	73/47/Q
MgH_2				61/24/N	
ZrH_2				59/70/N 60/50/N 84/50/N	

[a]The three terms represent: run number/percent by weight of fuel/ burning characteristic of the mix, IV - smooth burning, quantitative computer output available, Q-smooth burning, no quantitative computer output available; B-uneven combustion or poor ignition, N-failed to ignite.

[b]Ternary mix containing 10% by weight calcium resinate.

Table VIII. Injection Parameters and Base Drag Reductions for Smooth-Burning Mixes with No Quantitative Computer Output

Run	Composition	I	$\%\Delta C_{Db}$ reduced
68	$NaBH_4/Sr(NO_3)_2$(25/75)	0.011	45
83	$NaBH_4/Sr(NO_3)_2$(40/75)	0.005	51
77	$Mg/KClO_4$/C.R.[b](37/53/10)	0.002	31
79	$Mg/KClO_4$/C.R.(37/53/10)	0.003	46
81	$Ti/Sr(NO_3)_2$/C.R.(32/58/10)	0.012	57
74	$Zr/KClO_4$(57/43)	0.019	59
73	$Zr/Sr(NO_3)_2$/C.R.(47/43/10)	0.003	32

Run 66	tb, sec	m, g	I
igniter + fumer	11.2	8.6	0.002
fumer	9.4	7.8	0.0022

For the faster burning mixes, the correction is more substantial as shown for a $NaBH_4/Sr(NO_3)_2$ mix.

Run 56	tb, sec	m, g	I
igniter + fumer	2.4	10.2	0.011
fumer	1.4	9.4	0.018

On this basis the results in Table VIII generally follow the trend that the faster-burning mixes yield higher base-drag reductions than the slower burning mixes.

V. CONCLUSIONS

1. Base pressure increase from pyrotechnic combustion can be correlated by the injection parameter.

2. Maximum base pressure increase at $M_\infty = 2.0$ occurs near an I value of 0.002. The maximum base pressure increase corresponds to a 68% reduction in the base-drag coefficient.

3. Specific impulses of nearly 8 kN-s/kg have been observed with fumer mixes with injection parameters near 0.002.

4. Specific impulses measured with a force balance are in reasonable agreement with the specific impulse computed by integration of base pressure vs time curves. This implies the pressure distribution is uniform over the base of the wind tunnel model.

5. The use of $NaBH_4$ as a fuel yielded a fumer mix that burned rapidly and smoothly, but did not provide a fumer fuel much different than a magnesium-based fumer mix with the same burning rate.

REFERENCES

1. J. R. Ward, F. P. Baltakis, S. W. Pronchick, "Wind Tunnel Study of Base Drag Reduction by Combustion of Pyrotechnics," BRL Report No. 1745, October 1974, (AD #B000431L).

2. J. R. Ward, F. P. Baltakis, D. Mancinelli, and T. Elmendorf, "Wind Tunnel Experiments on the Effect of Combustion in the Wake Region of Supersonic Projectiles," BRL Memorandum Report 2588, February 1976, (AD #B009982L).

3. J. Reid and R. C. Hastings, "The Effect of a Central Jet on the Base Pressure of a Cylindrical Afterbody in a Supersonic Stream," RAE Report No. Aero, 2621, 1959.

4. L. D. Kayser, "Effects of Base Bleed and Supersonic Nozzle Injection on Base Pressure," BRL Memorandum Report No. 2456, March 1975, (AD #B003442L).

5. J. E. Bowman and W. A. Clayden, "Reduction of Base Drag by Gas Ejection," RARDE Report 4/69, December 1969.

6. S. N. B. Murthy and J. R. Osborn, "Base Flow Data With and Without Injection: Bibliography and Semi-Rational Correlations," BRL Contract Report No. 113, August 1973, (AD #914188L).

7. R. H. Moore and R. K. Ziegler, "The Solution of the General Least Squares Problem With Special Reference to High-Speed Computers," Los Alamos Scientific Laboratory Report LA-2367, March 1960.

APPENDIX A

Summary of the Pressure-Time Histories for the Runs Which Ignited

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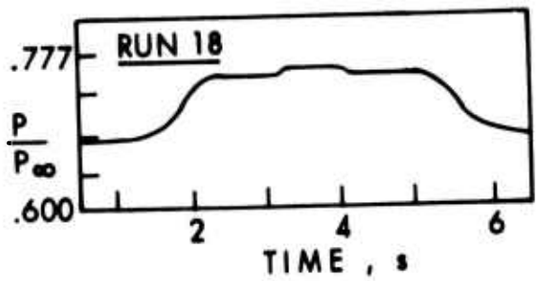

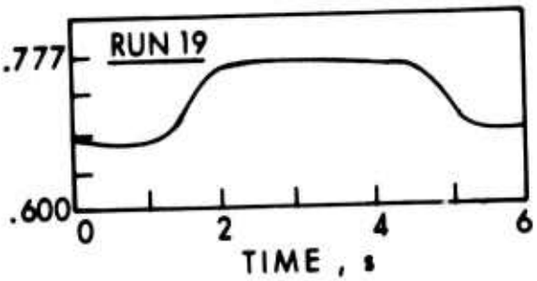

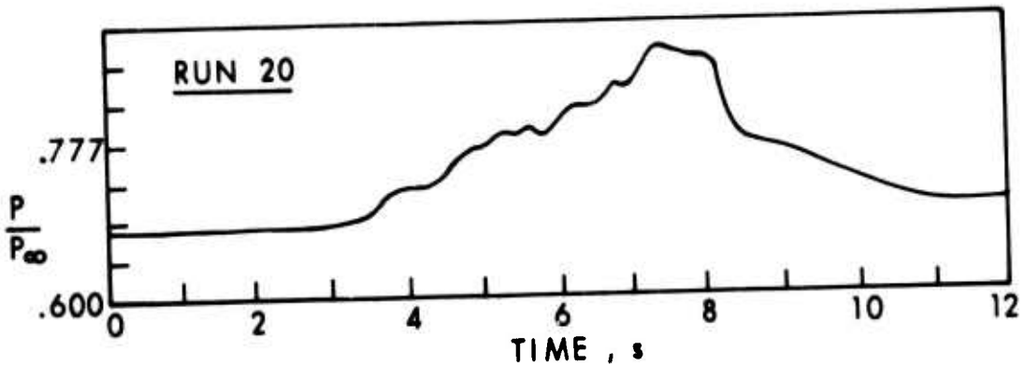

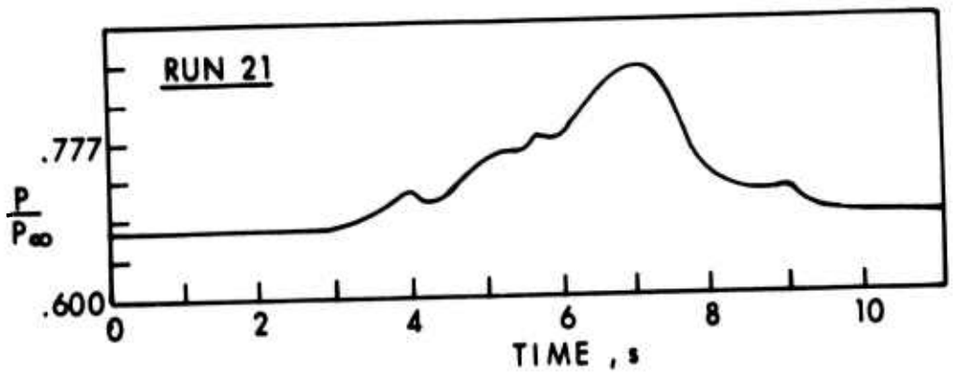

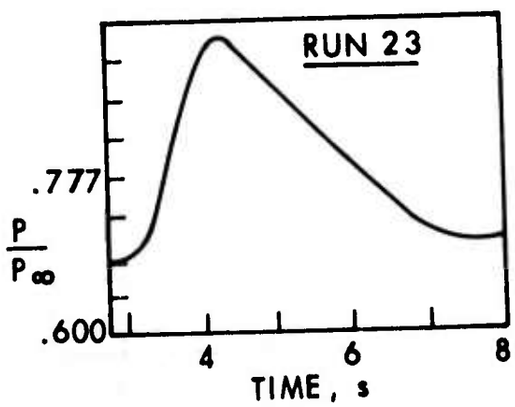

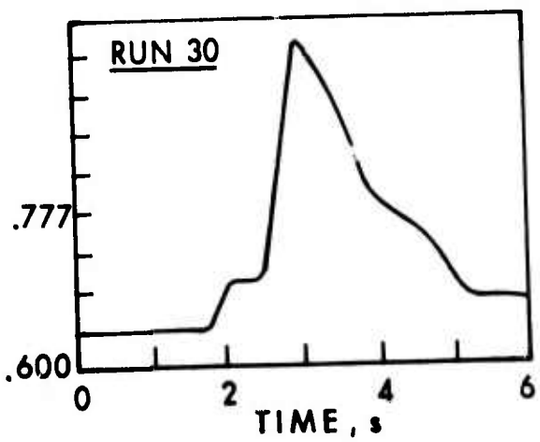

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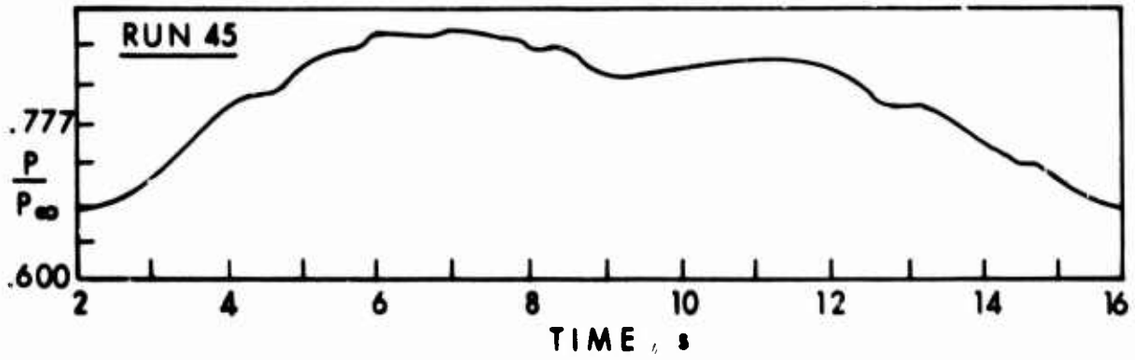
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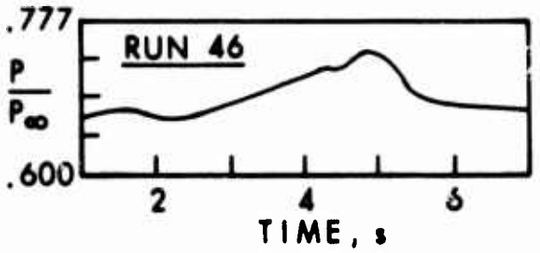
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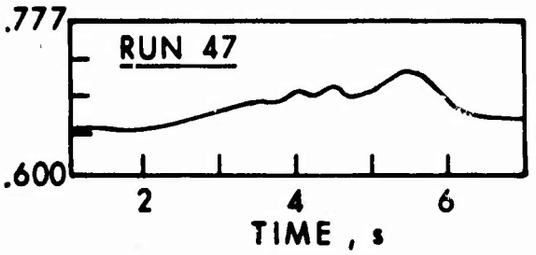
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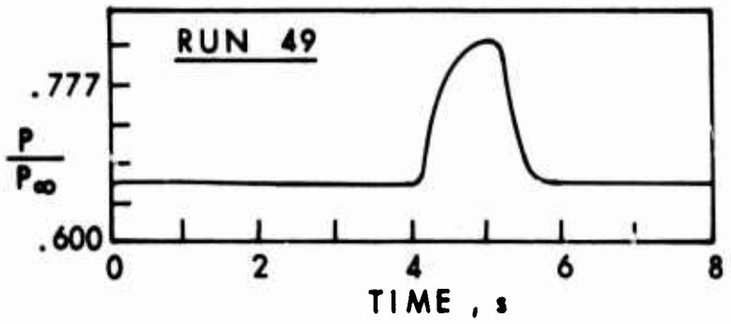
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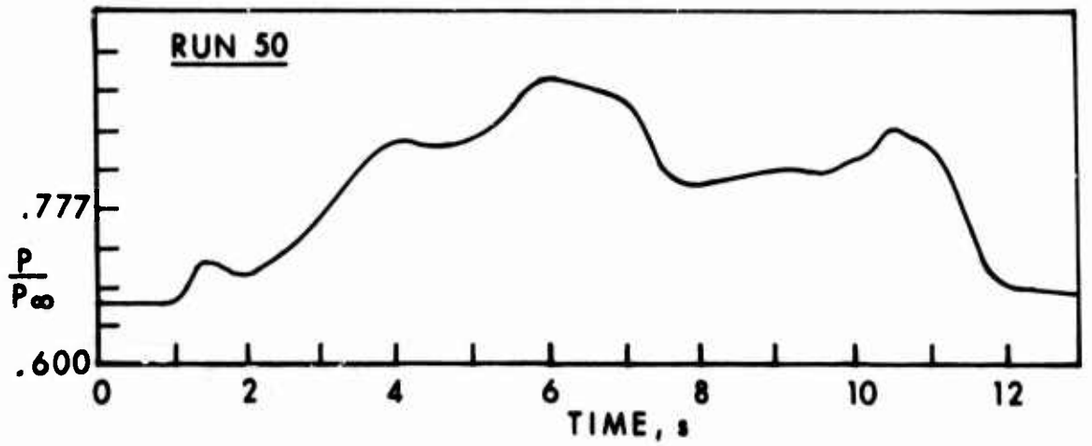
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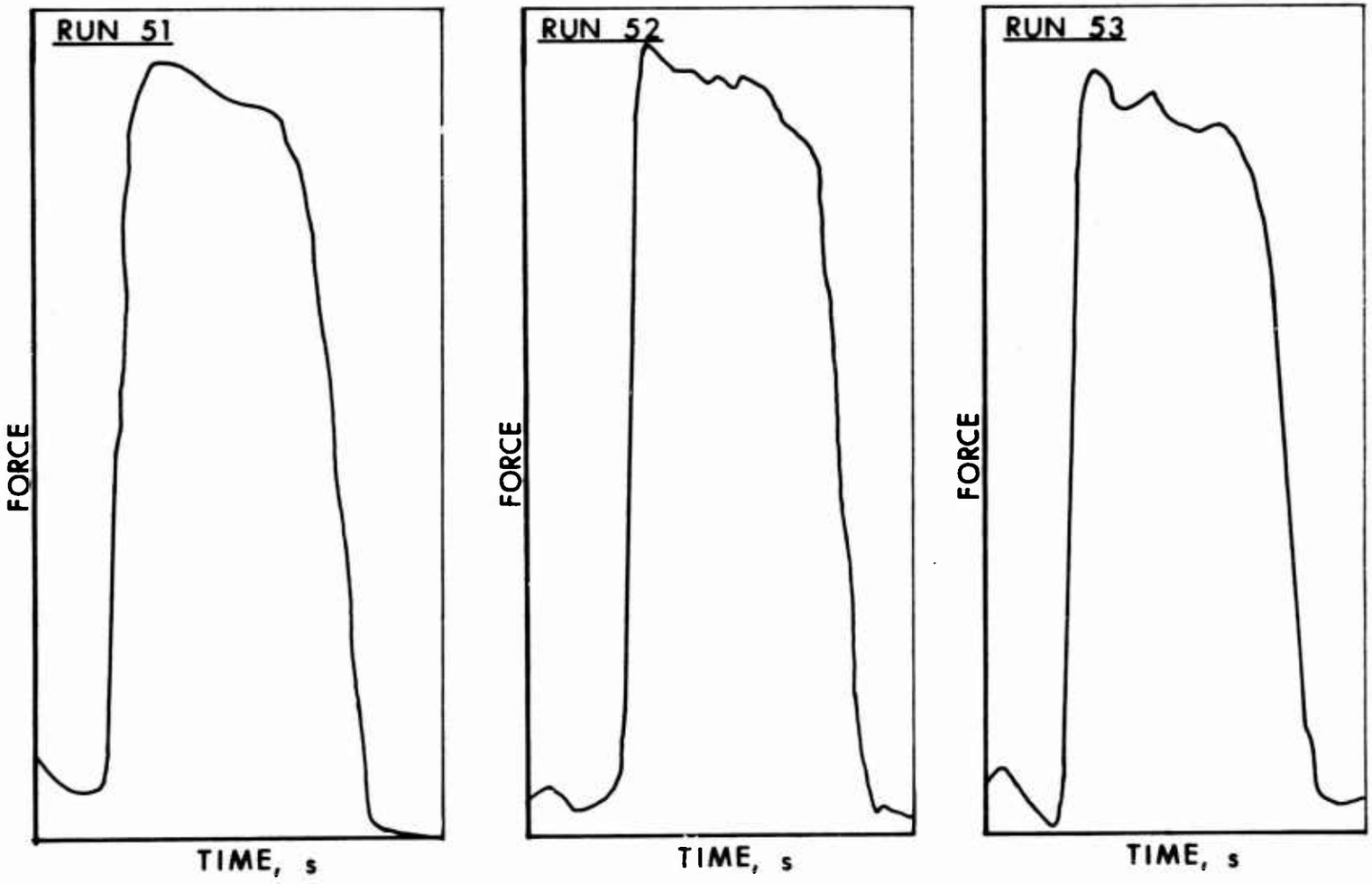
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TIME, s
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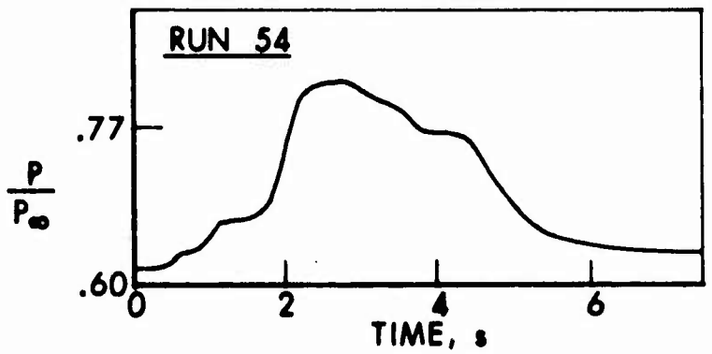
FORCE
TIME, s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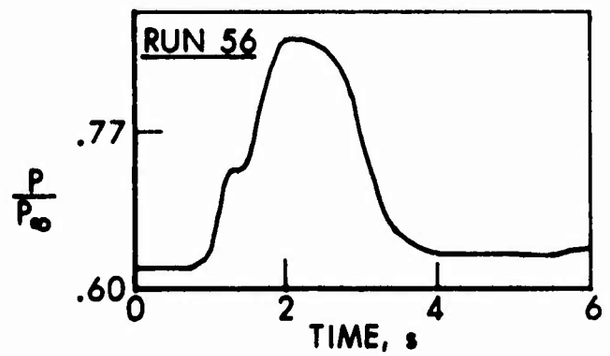
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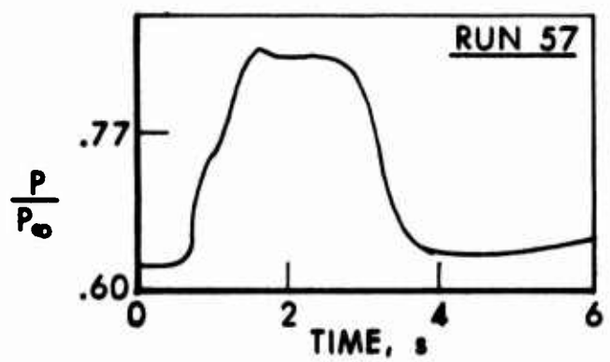
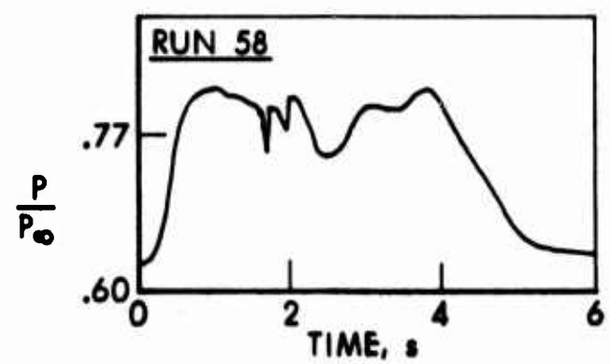
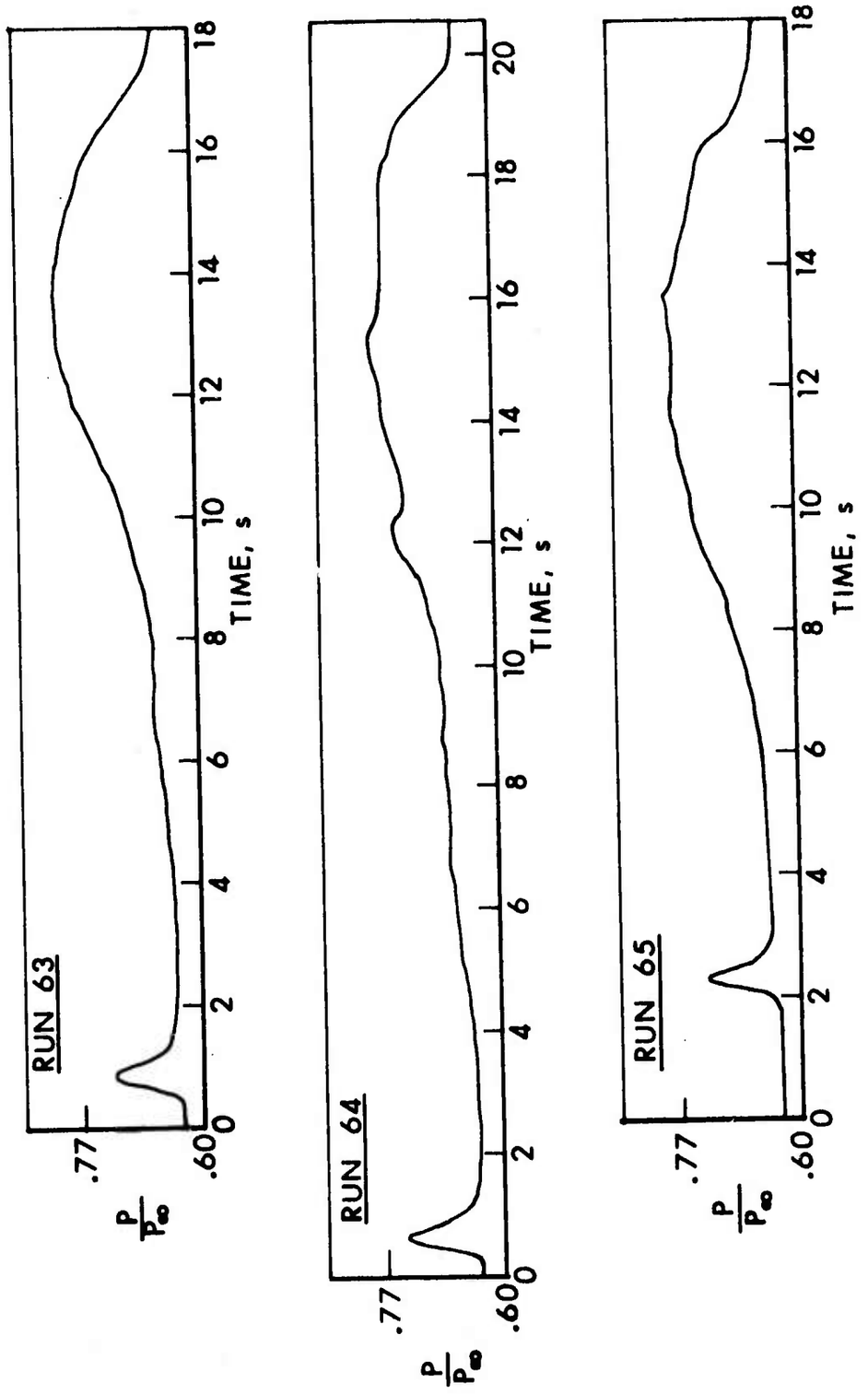
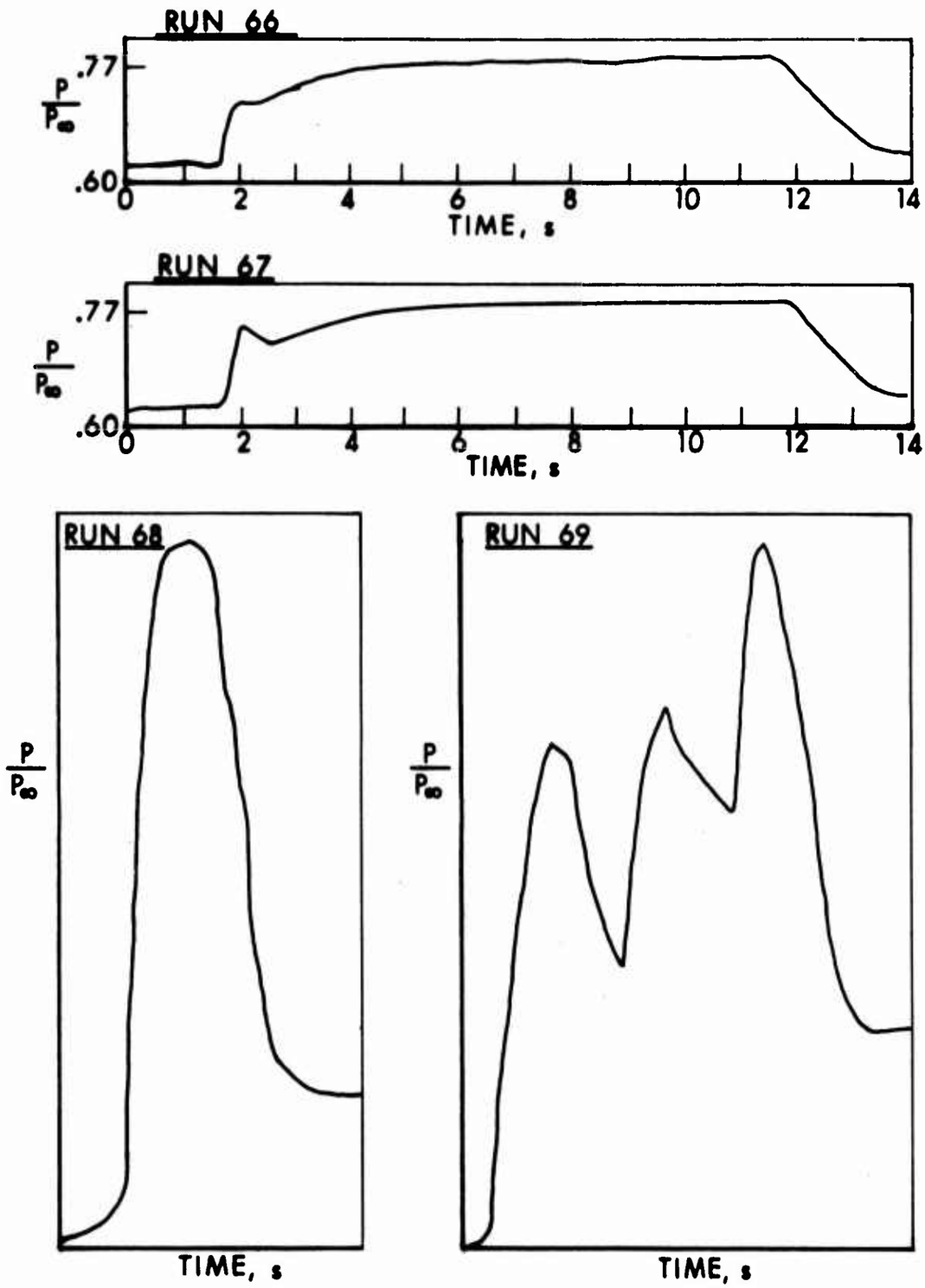
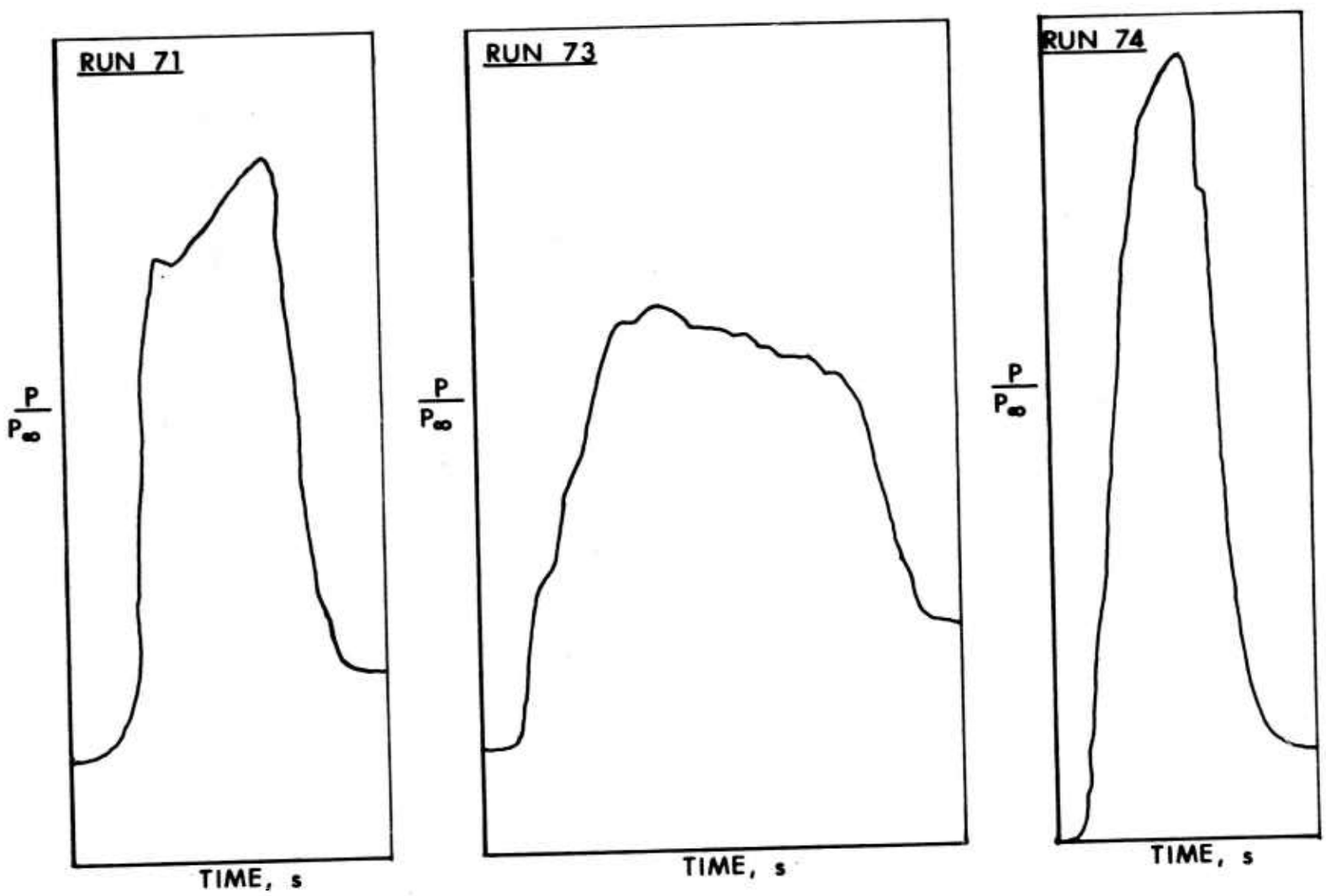
6
TIME, s

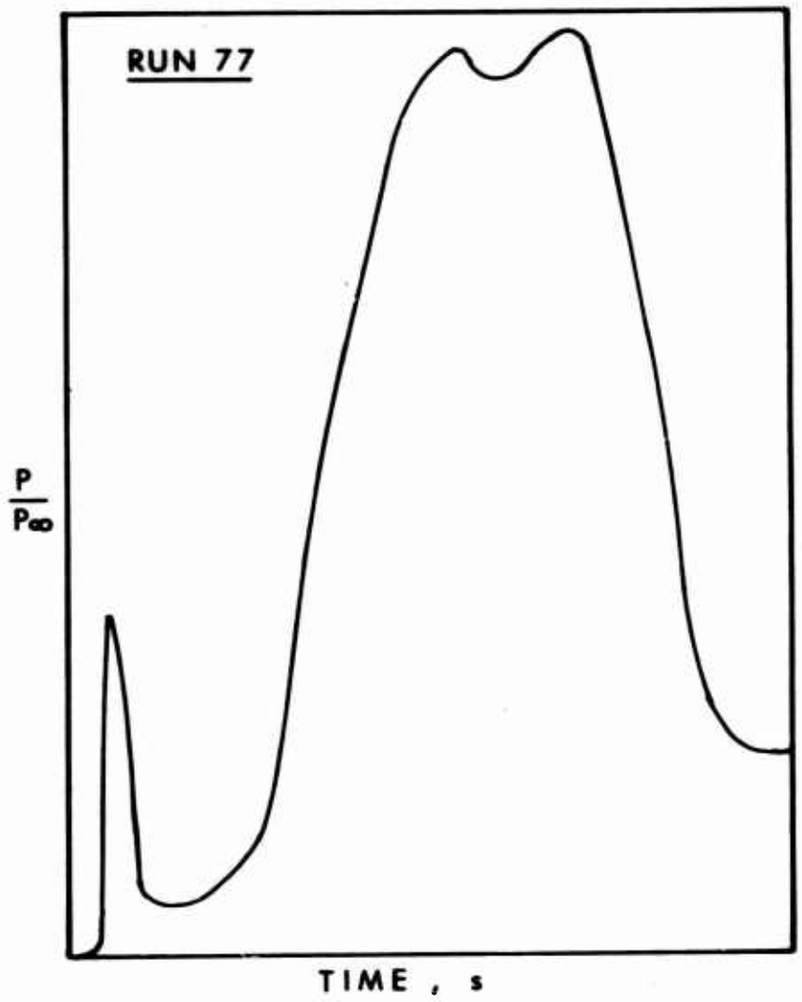

RUN 57
.77
.60
P/P∞
0
2
4
6
TIME, s

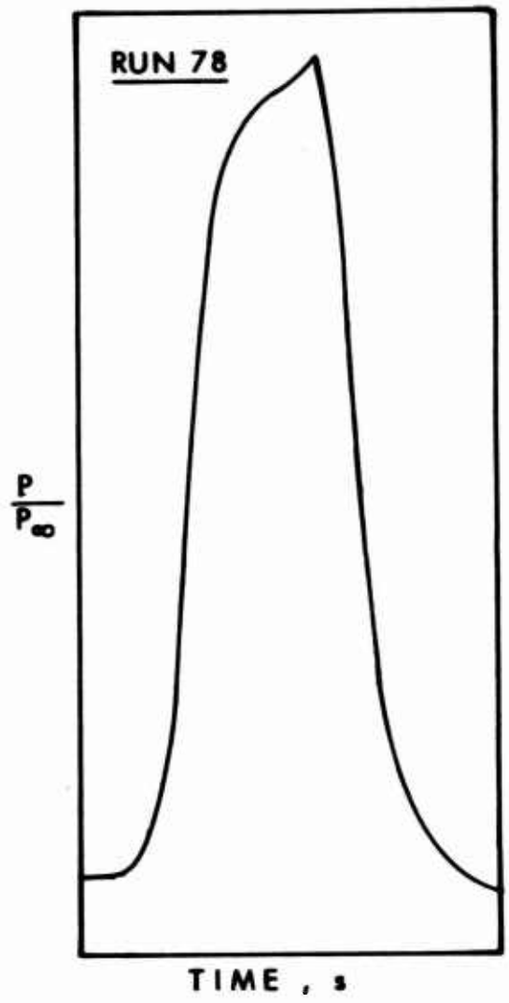

RUN 58
.77
.60
P/P∞
0
2
4
6
TIME, s

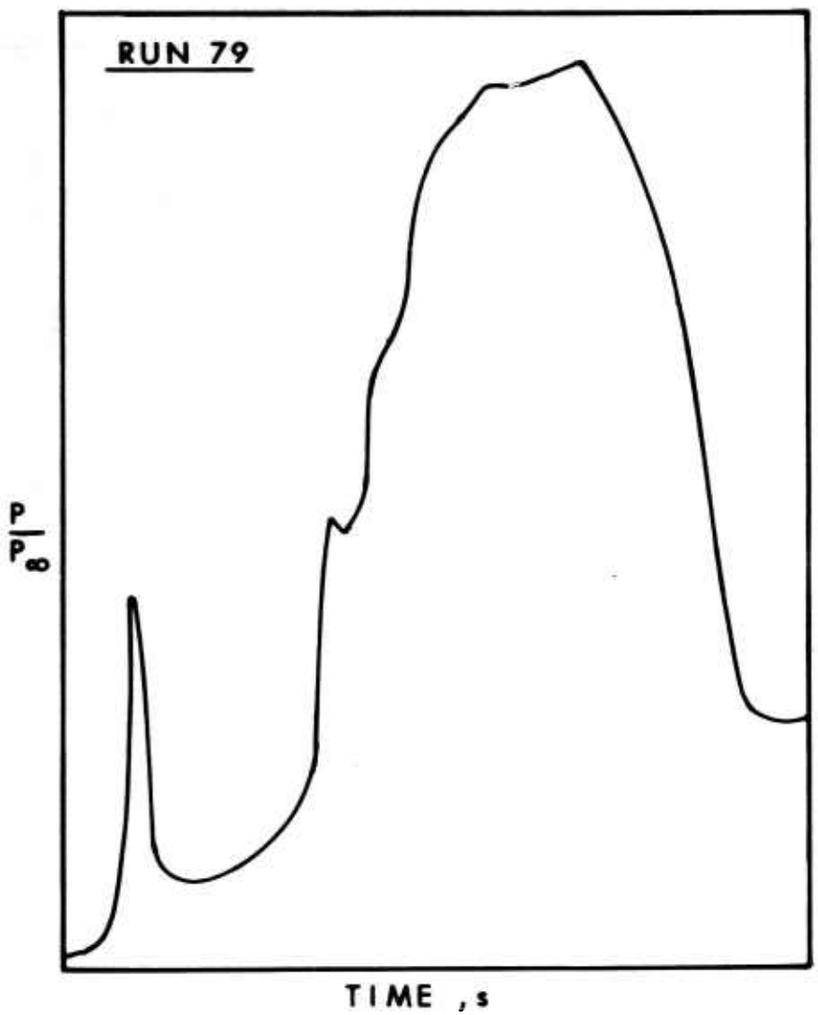

RUN 63
RUN 64
RUN 65
P/P∞
.77
.60
0
2
4
6
8
10
12
14
16
18
20
TIME, s

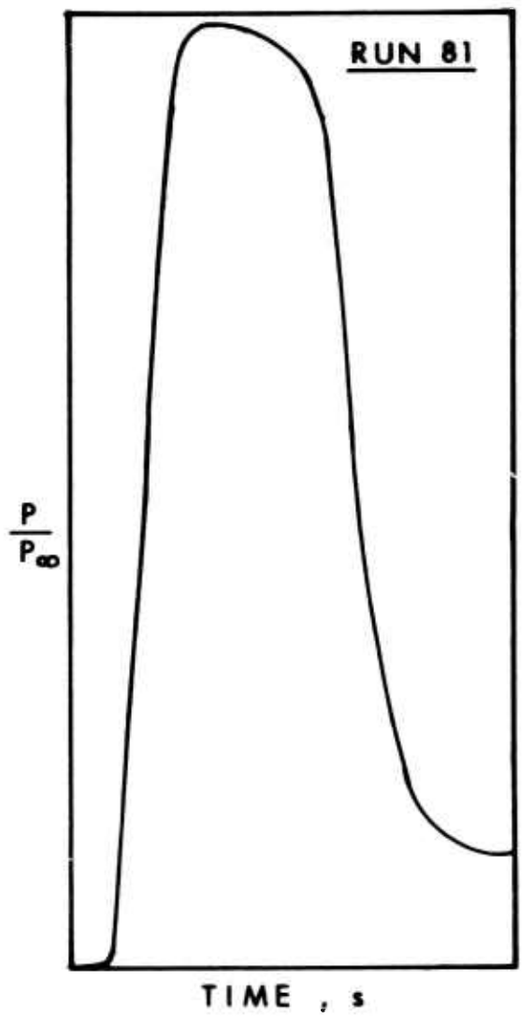

RUN 66
P/P∞
.77
.60
0
2
4
6
8
10
12
14
TIME, s
RUN 67
P/P∞
.77
.60
0
2
4
6
8
10
12
14
TIME, s
RUN 68
P/P∞
TIME, s
RUN 69
P/P∞
TIME, s

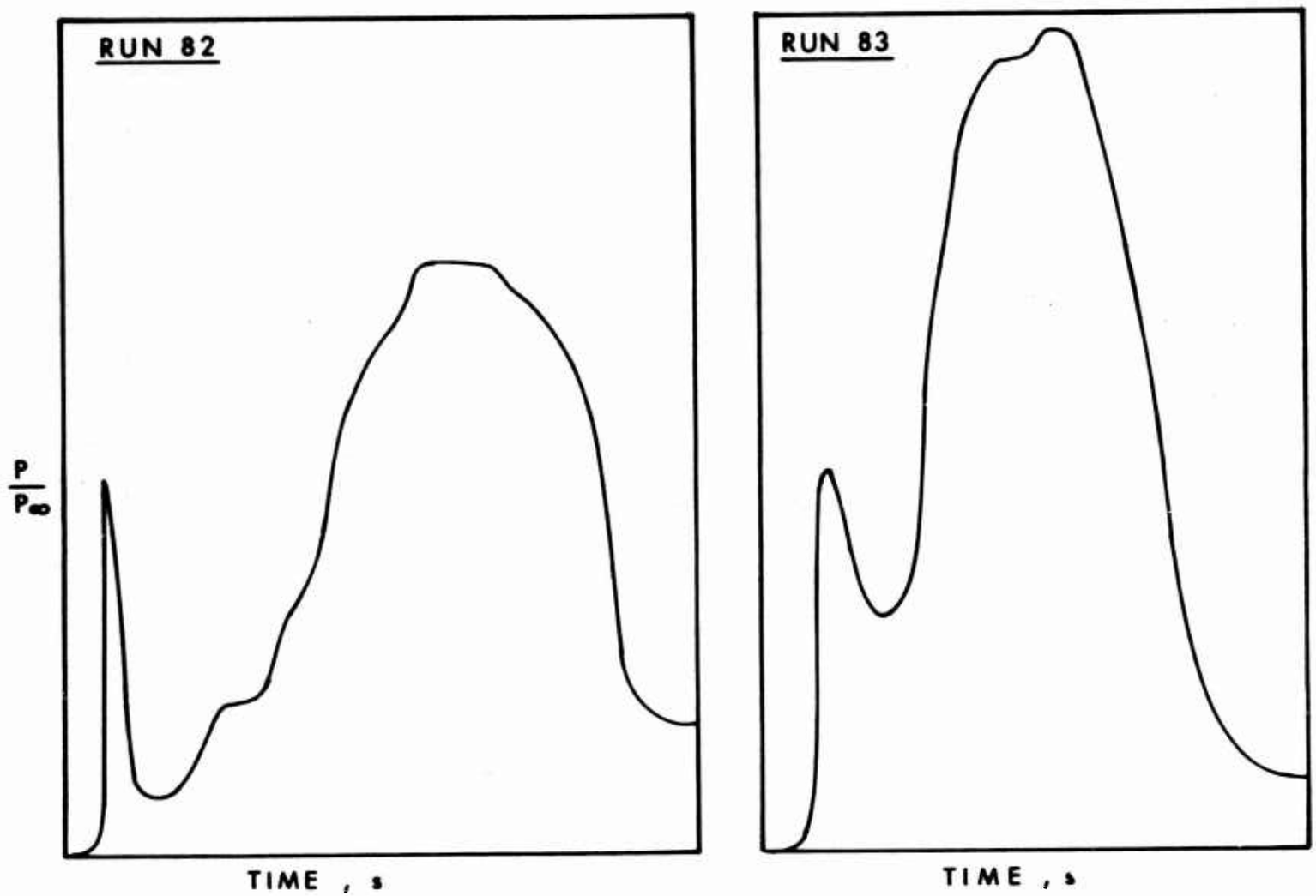

RUN 71
P/P∞
TIME, s
RUN 73
P/P∞
TIME, s
RUN 74
P/P∞
TIME, s

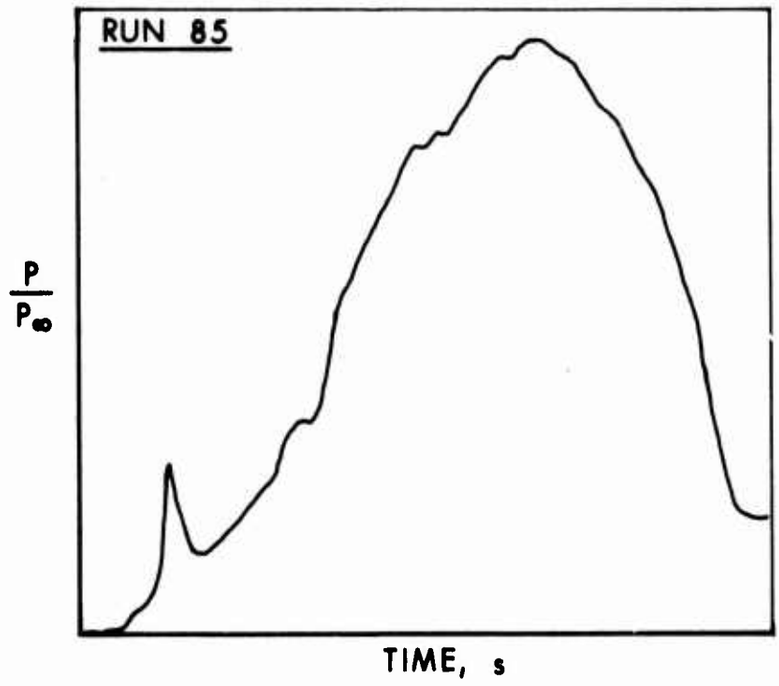

RUN 77
P/P∞
TIME , s

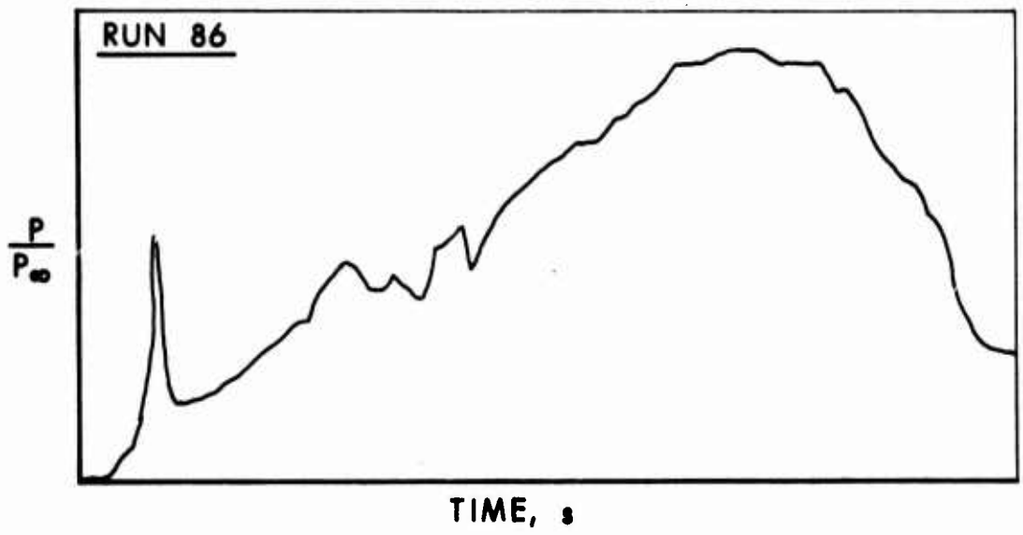

RUN 78
P/P∞
TIME , s

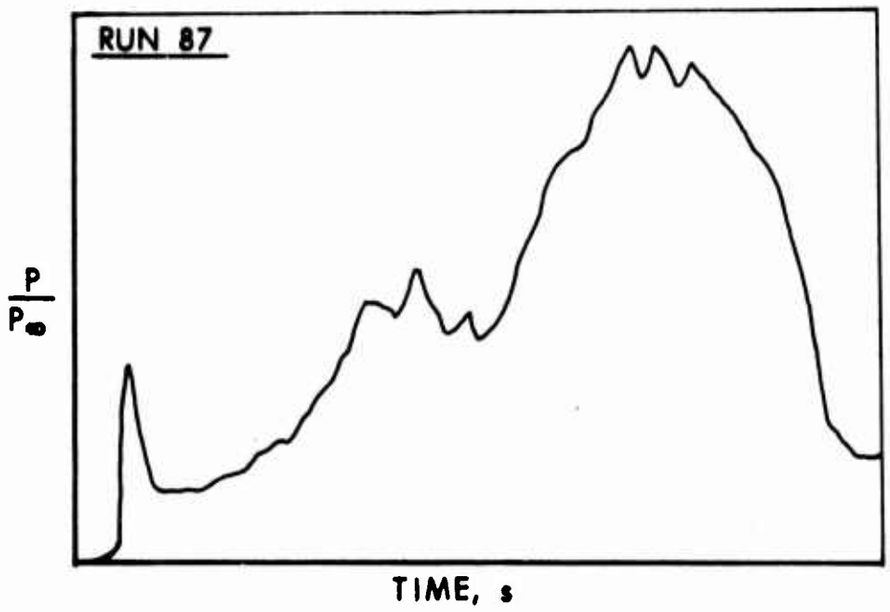

RUN 79
P/P∞
TIME , s

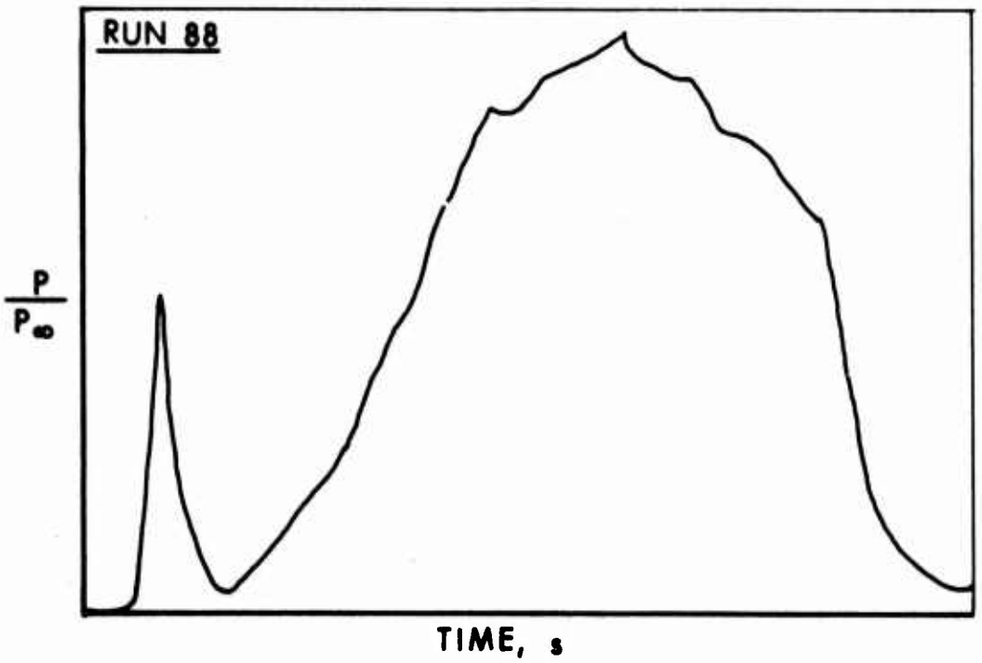

RUN 81
P/P∞
TIME , s

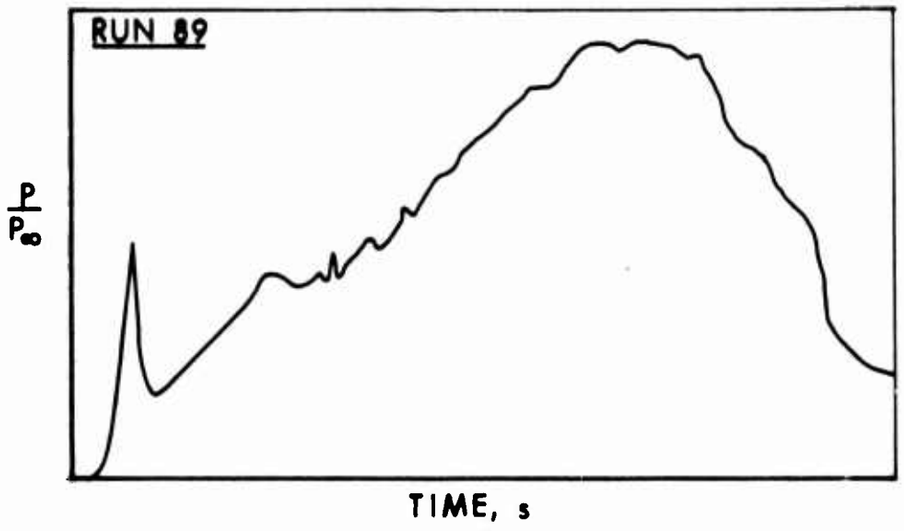

RUN 82
P/P∞
TIME , s
RUN 83
TIME , s

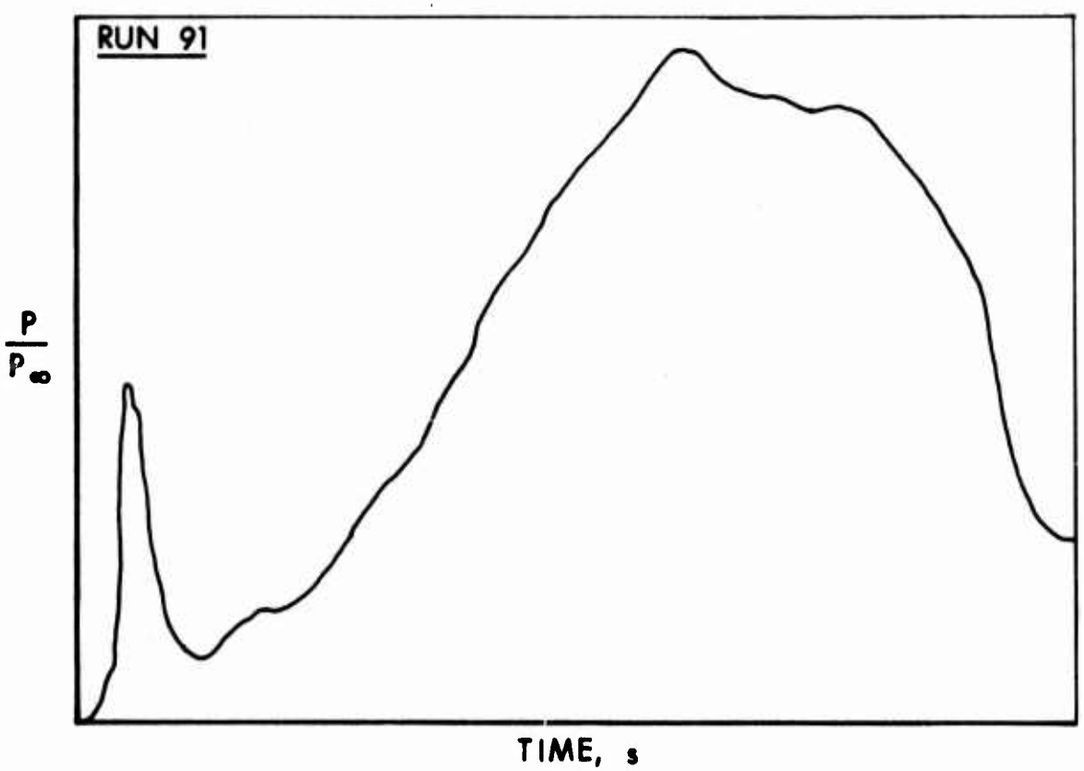

RUN 85
P/P∞
TIME, s

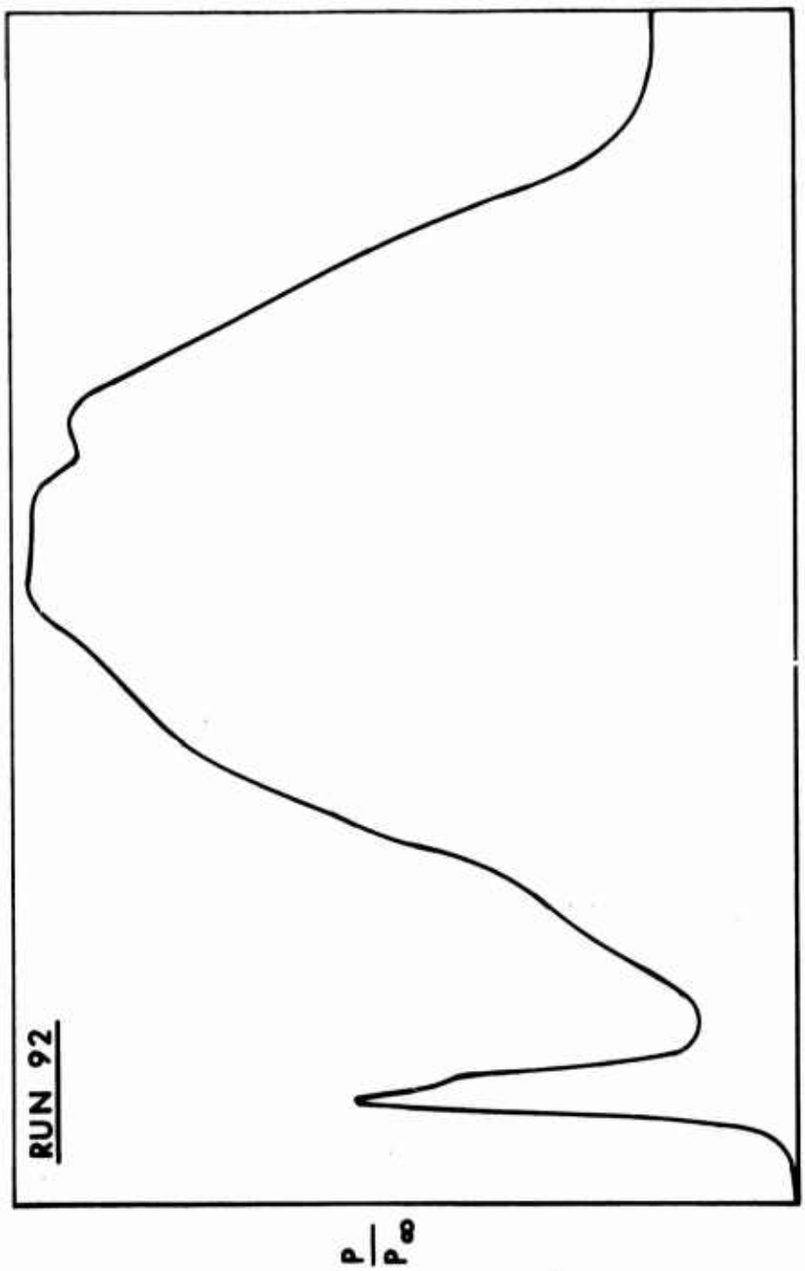

RUN 86
P/P∞
TIME, s

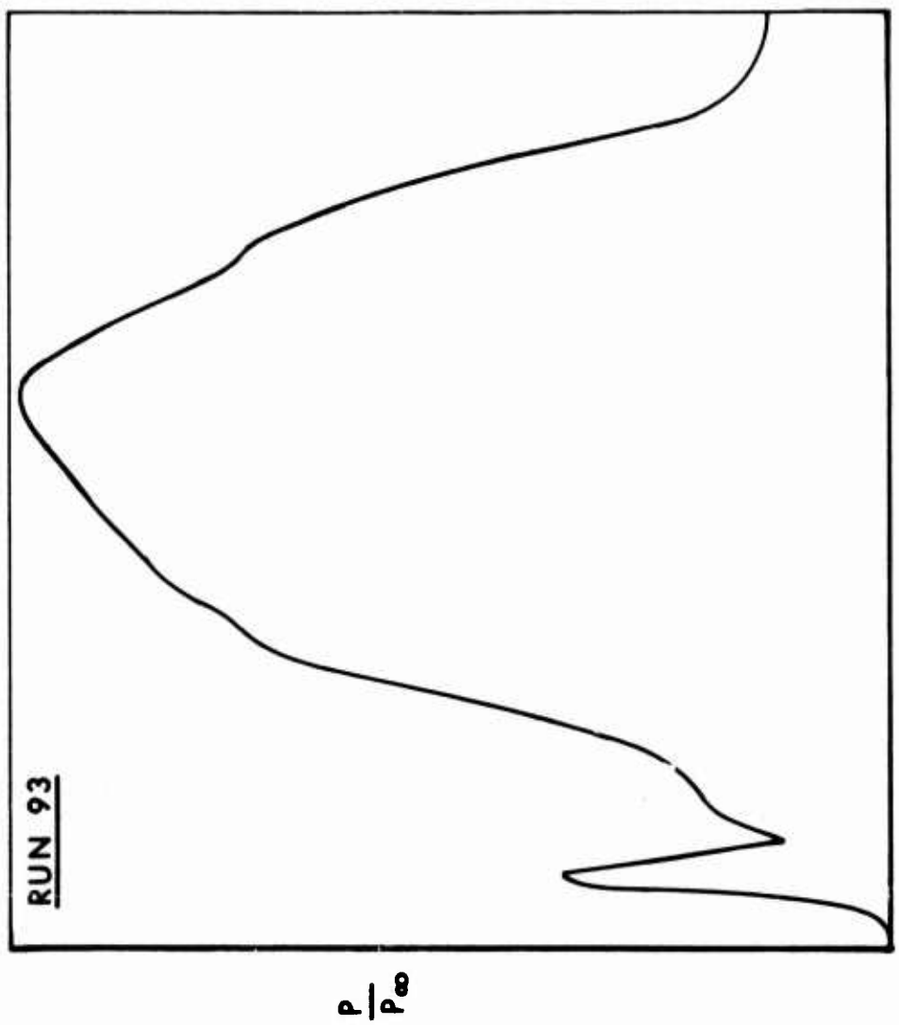

RUN 87
P/P∞
TIME, s

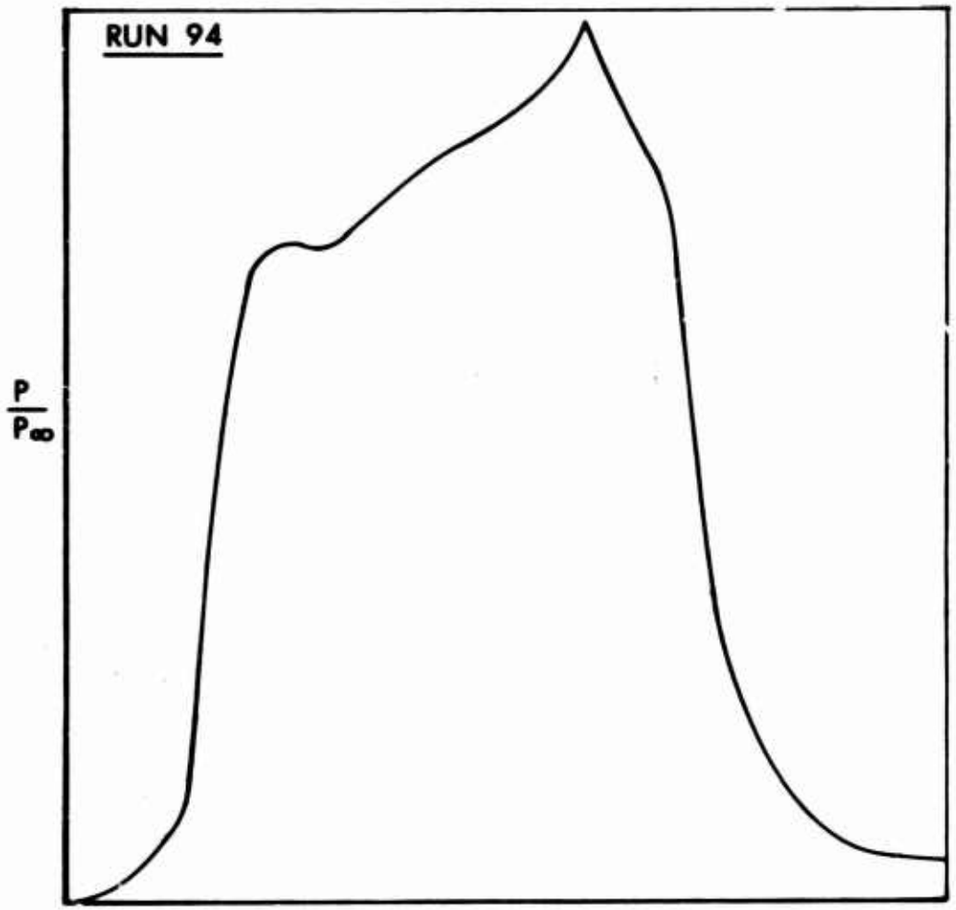

RUN 88
P/P∞
TIME, s


RUN 89
P/P∞
TIME, s


RUN 91
P/P∞
TIME, s


RUN 92
P/P∞
TIME, s


RUN 93
P/P∞
TIME, s


RUN 94
P/P∞
TIME, s

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